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REPORT OF THE
BOSTON SOCIETY OF CIVIL ENGINEERS
COMMITTEE ON FLOODS



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REPORT OF THE BOSTON SOCIETY OF CIVIL ENGINEERS' COMMITTEE ON FLOODS

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- S. S. KENT, Lowell, Mass., *Secretary*.
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- W. A. Liddell, Federal Power Commission, Washington, D. C.
- Charles W. Sherman, Metcalf & Eddy, Boston, Mass.
- T. J. Rouner, New England Power Service Co., Boston, Mass.
- Frank E. Winsor,* Chief Engineer Metropolitan District Water Supply Commis-
sion, Boston, Mass.

1937

- A. H. Morrill,* Chief Engineer, Boston & Maine Railroad, Boston, Mass.
- Capt. James H. Stratton, U. S. Engineer Office, Boston, Mass.

1938

- Lt.-Col. M. J. Young, U. S. Engineer Office, Providence, R. I.

1939

- Col. W. L. Bragdon, U. S. Engineer Office, Providence, R. I.
- Lt.-Col. A. K. B. Lyman, U. S. Engineer Office, Boston, Mass.

1941

- Col. H. Latson,* U. S. Engineer Office, Providence, R. I.

The publication of this report is made possible by the fund established by
the late John R. Freeman.

*Deceased

REPORT OF THE COMMITTEE ON FLOODS

CHAPTER I

Chapter I. Introductory.

This committee was appointed by President Harold K. Barrows after the great flood of 1936, upon authorization by the Board of Government at a meeting held April 6, 1936.

The committee's first work was the compilation and distribution of a list of agencies collecting flood data. Chief among these were the Water Resources Branch of the U. S. Geological Survey and the United States Army Engineers working on the flood control projects. Until these data, particularly of the former, were available it was difficult for the committee to make much progress in its study.

Meanwhile, in 1937, the subject of the flood control projects for New England became very active with the negotiations for the development of reservoirs under "State compacts". The committee, chiefly through its sub-committee on flood control projects for New England, thoroughly discussed the question of whether it should publish any opinion with respect to this problem. It was decided, however, as stated in its second report to the Society "that even if an opinion could have been reached by the committee at that time no useful purpose would be served by its publication."

Not long after the publication of the data on the 1936 flood, another major flood, the "Hurricane Flood of 1938", occurred. It was decided that the committee's investigation should be extended to include this flood. As soon as the data on this were available the committee was able to proceed. A preliminary report in typewritten form was presented to the Society at the Annual Meeting on March 19, 1941, and is on file at the Society rooms.

The Society's previous flood committee appointed after the 1927 flood published in 1930 a report covering not only descriptions and engineering data of the storm rainfall, the flood and the flood damage, but also a general engineering study of the whole subject of floods in New England and developed a flood formula based on the flood hydrograph. This analysis, which also included the development of a flood characteristic curve, by its emphasis on the flood hydrograph as a measure of the flood producing characteristics of a given stream, may

be said to have laid the foundation of the most of the modern methods of flood analysis.

The present report is being published with the following general objects in view:

(1) To assemble in one volume general information on the recent New England storm rainfalls and floods, including descriptions and pertinent data, with a list of additional references where more detailed data can be found.

(2) To summarize the progress of the engineering studies of the flood problem including flood rainfall and runoff prediction, determination of design floods, flood routing, flood frequency, etc., and to express as far as possible what is considered the committee's judgment on the various present methods in use.

(3) To summarize the extensive work that has been done and is proposed for the prevention and control of floods in New England.

(4) To describe the present arrangements for flood warnings and handling of flood emergencies that are now in force in the New England states.

The report is divided into chapters, each dealing with a single subject. These chapters are largely the work of various sub-committees, a list of which is given at the end of the report. Some of these chapters include bibliographies. These bibliographies are not necessarily intended to be complete, but represent what the committee considers the significant references for each subject given. A brief summary of the contents of each chapter follows:

Chapter II. General Description of the 1936 and 1938 Floods in New England.

This chapter compares the floods of 1936 and 1938 with that of 1927. Those of 1927 and 1938 were both caused by heavy storm rainfall, one in the northwestern part of New England and the other in the south central part, while that of 1936 was caused by a general rainfall and melting snow superimposed on rivers already full. All of these were record floods in some parts of New England and that of 1936 ranks with the very great floods of the country.

Chapter III. Storm Rainfall, Data and Maps.

This chapter discusses the storm rainfall that caused the floods of 1927, 1936 and 1938. It also contains a history of the great

storms of New England, carrying this forward from the report of the previous Flood Committee.

Included also, are the summaries of the results of a preliminary study by the Weather Bureau entitled "Maximum Possible Precipitation Over the Ompompanoosuc Basin Above Union Village, Vermont". These maximum figures are of great interest as giving a limit, determined, not by the extension of past records but from a theoretical study of probable precipitation from a meteorological point of view. They furnish a point at which predictions of rainfall intensity may be terminated for a given area and period.

Chapter IV. Flood Runoff Data — 1936 and 1938.

There is summarized in this chapter data regarding the flood flow, flooded areas and river profiles with references showing where more detailed information can be obtained. There is also a section giving the results of a study of the effect of existing storage on flood flows which shows to what extent reservoirs constructed for other purposes were of benefit in reducing the peak flows on the rivers below them.

Chapter V. Flood Runoff Analysis.

This chapter analyzes the hydrology of floods and the various methods of their prediction and computation of flows.

Flood Hydrograph and B. S. C. E. Flood Formula.

The 1930 report proposed the following form for a flood formula applicable to New England:

$$Q = C_f \sqrt{A R} \quad \text{where}$$

Q = the peak flow in c.f.s.

C_f = a flood coefficient

A = the drainage area in sq. mi.

R = the total flood runoff in inches on the drainage area

It was shown that the coefficient used in this formula could be determined from a flood hydrograph of a flood of any size, caused by a storm the length of which is less than the concentration period, and it was pointed out that the flood peak of any such flood was proportional to the total runoff.

The developments in flood hydrograph analysis since the 1930 report are described, including the unit hydrograph and distribution graph and more recent analyses. The results of these methods are compared with those originally given in the 1930 report.

Flood Routing.

When the 1930 flood report was prepared, the subject of flood routing had hardly been considered. It has now become a well developed method of great assistance in all flood studies.

Spillway Design Flood.

The spillway of a dam should be so designed as to discharge floods of certain magnitude called the "spillway design flood". The abutments of many dams were overtopped by the 1936 and 1938 floods. In 1936, this happened on some of the main dams on the largest rivers in New England. Fortunately, the resulting damage was not great, as prompt measures were taken to prevent washouts. These floods were apparently larger than the engineers had considered likely. The modern flood analysis, coupled with these recent floods, has made possible with considerable more confidence, the proper design of the spillway to pass any flood. The same principles apply as were pointed out in the last report: that a large important structure, the failure of which would cause a great disaster, must be designed to take a maximum flood, but less important structures may be designed to take lesser floods. The report points out that there is a certain risk in prescribing sufficient spillway capacity to take a flood resulting from maximum possible rainfall and runoff, added to maximum possible snow melt, combined with heavy freeboard allowance for frost and waves, as this may well result in a design flood of such magnitude that would make the building of most dams prohibitive in cost.

Rainfall-Altitude Relations.

Rainfall-altitude relations, based on the more recent records obtained, are compared to those given in the previous report of the committee. The committee again wishes to urge the advisability of establishing more high-altitude recording rainfall gages.

Runoff from Melting Snow.

Much data on melting snow have been obtained since the last report. Ten years ago, snow surveys in New England were rarely made. Today, they are made regularly and are of great value in predicting stream flows.

Flood Frequency.

In the last ten years there has been a great deal of work done

in analyzing the frequency of flood flows by statistical methods. These methods have been applied to the large New England rivers for which records are available for nearly 100 years. The conclusion has been reached that 100 years of record are inadequate to accurately extend frequency curves. The conclusion is also reached that the frequency of floods has no bearing on what the design flood for a given project should be. They are, however, of importance in assessing the economic benefits of flood control works and therefore must be used, but the committee recommends that the results can justify the use of only the simplest methods.

The committee makes no attempt to fix the frequency figure for the 1936 flood beyond the statement that it was a flood of a magnitude that might be expected once in several hundred up to possible one thousand years.

Chapter VI. Flood Losses and Economics.

In this chapter are presented the figures of the flood damages sustained in the recent floods and also a description of the type of damage caused to water supplies in various communities. There is also included a general discussion of methods of estimating flood damage and benefits. Damages are generally figured from estimates of the actual damage caused, plus an allowance for indirect damages covering estimates of contingent items. The totals used by the War Department, notably in the Connecticut River, include, in addition to the direct and indirect damage, an item for intangible benefits, determined from depreciation of real estate values. Whether this method of determining intangible damages is reliable, the committee is unable to agree.

Chapter VII. Flood Control Programs and Work.

This chapter describes the work done and proposed on flood control and flood prevention on the various rivers in New England. Most of this work has been done by the Federal Government in charge of the Army Engineer Offices at Boston and Providence, although considerable has been done by the Commonwealth of Massachusetts and some by other states and communities. The 1930 flood report concluded that no general flood control scheme would be economical in New England, though reservoirs built for a combination of uses could probably be worked out and suggested the establishment of water regulation districts for this purpose.

The 1936 flood produced a great public demand for flood protection and control. This report compares the State compact plans originally proposed for this work with the complete Federal ownership plan finally adopted. While some of the committee question whether the great cost of the whole flood control projects can be justified economically, there is no question as to the benefits that will result from the work done and proposed, most of which was started at the time when a large public works program was required to relieve unemployment.

Chapter VIII. Flood Warnings and Flood Emergency Provisions.

This chapter describes the present arrangements regarding flood warnings and handling of flood emergencies now existing on various river systems in the different New England states. On most of the large rivers the initial source of flood information and warning comes from the men operating the plants on the rivers who are the most competent to predict what is likely to occur. The problem of distributing flood information to the inhabitants of the river valleys is dependent upon the nature of the development in those valleys. A description is given of the system now in use in Pennsylvania which is probably too expensive for application in New England. Massachusetts now has the most elaborate system in New England.

CHAPTER II

General Description of the 1936 and 1938 Floods in New England

Within the past fourteen years, New England has experienced three great floods, in November, 1927, March, 1936, and September, 1938.

The flood of November, 1927, was caused by a single rainstorm of great severity and reached its great intensity on the streams rising in the Green Mountains and the Berkshire Hills.

The floods of March, 1936, resulted from the combination of rainfall plus melting snow which cause the usual spring freshets, but in a greatly aggravated form. The most notable flows occurred on the larger rivers along the Atlantic Coast from the Penobscot to the Susquehanna.

The September, 1938, flood resulted from a four day storm culminating in a rainfall of great intensity which accompanied a hurricane. It was most severe in Connecticut, Central Massachusetts, and portions of Southern New Hampshire and Vermont.

CLIMATOLOGICAL CAUSES

The history of great storms in New England shows that many of them have resulted from the same basic meteorological phenomena. Normally, warm tropical moisture-laden air masses move west from the West Indies to the coast of Florida, and then follow up the coast to Cape Hatteras and from there are forced northeasterly over the Atlantic Ocean by high pressure areas along the Middle Atlantic coast. At times the normal northeast path of the air masses is diverted by high pressure areas off the coast and the moisture-laden front continues directly north over New Jersey and New England. If the advancing warm front is confined further by high pressure areas from the west and north, then as the warm front climbs upward over the cold fronts, a heavy precipitation results over the New England area, the amount of the rainfall depending on the relative movement of the encroaching cold fronts. This abnormal movement of warm and cold fronts has characterized the excessive precipitation of the storms of November, 1927, March, 1936, and September, 1938.

FLOODS

The following is a discussion of the outstanding floods on the major New England drainage areas. In this discussion are included not only the three recent floods, but also some of the older, notable records.

Penobscot River

On the Penobscot River the maximum flood of record was that of May 1, 1923. At the Bangor dam, drainage area 6,700 square miles, the flow was 154,000 c.f.s., or 23 c.s.m. Prior to 1936, this was the outstanding flood on any of the larger New England rivers. The rainfall was only 3.8 inches, but the runoff included a considerable amount of melting snow produced by warm weather in the two weeks preceding.



PLATE I.—ICE AT BANGOR, MAINE, ON THE
PENOBSCOT RIVER, 1936.

The 1936 flood peak at Bangor was 130,000 c.f.s., and at the West Enfield gaging station, 125,000 c.f.s. Above the latter station the rainfall was 2.6 inches during the first storm, 1.85 inches during the second storm, and 5.3 inches for the entire period March 9 to 22. In addition, the run-off included a large but undetermined

amount of melting snow. The large amount of water stored on the West Branch, about 13.5 billion cubic feet, was an important factor in reducing the flood peaks.

The largest floods of the Penobscot River are as follows:

May 1, 1923	153,000 c.f.s. at West Enfield
March 21, 1936	125,000 c.f.s. at West Enfield
April 10, 1901	115,000 c.f.s. (at Bangor)
May 2, 1907	93,400 c.f.s. at West Enfield

Kennebec River

The floods of March, 1936, on the Kennebec River were notable for two reasons:—

1. Because substantially all of the run-off from the water-shed above Moosehead Lake was stored during the flood period, this area contributed no run-off to the flood peaks.
2. Most of the damage occurred during the first phase of the flood and was caused primarily by ice jams. While ice damage was present on the entire river below Shawmut, the most serious ice jams and resulting damage occurred in the tidal portion below Augusta. It was here that the ice took out the piers of the Richmond-Dresden bridge and moved three of the 250-foot spans down-stream, one of them a quarter of a mile.

On March 9, the average depth of the snow cover was about 38 inches, with a water equivalent of nearly 10 inches. The rainfall in the period March 10 to 12 averaged 2.8 inches on the area above Waterville. This rainfall, falling on snow which had started to melt below the Forks, produced a peak at Waterville of 72,700 c.f.s. on March 13. The corresponding peak at Bingham Dam was only 13,500 c.f.s., indicating that the drainage area between these two points contributed a unit run-off of about 35 c.f.m.

The average precipitation in the second storm was 2.55 inches on the watershed above Waterville, N. H. At the same time, temperatures as far north as Greenville rose to above freezing, which melted most of the remaining snow cover. As a result, the river again rose and reached a peak at Waterville, drainage area 4260 square miles, on March 19, of 154,000 c.f.s. which is equal to 36.1 c.s.m. on the entire watershed. During this second phase of the flood, because substantially all the run-off from above Moosehead Lake was stored in that lake, the peak flow at Waterville, 154,000 c.f.s., came from the

3,030 square miles below Moosehead Lake. This makes the unit flow from this area 50.8 c.s.m. which constitutes one of the highest flows from a drainage area of this size.

This is the second highest flood which has occurred since 1832. Arranged in order of magnitude, the great floods at Waterville have been as follows:

December 1, 1901	157,000 c.f.s.
March 19, 1936	154,000 c.f.s.
May 22, 1832*	140,000 c.f.s.
May 1, 1923	135,000 c.f.s.
March 2, 1896	113,000 c.f.s.
April 15, 1895	103,000 c.f.s.

Androscoggin River

The flood of March, 1936, on the Androscoggin River exceeded any flood on record. In 1938 the Androscoggin River was north of the storm area.

In 1936 the floods were similar to the Kennebec River floods in that great damage was caused by ice jams, and the storage was a decisive factor in reducing their magnitude.

On this watershed the data on snow cover are very complete. At the end of the winter it averaged about 40 inches with a water content of about 10 inches. The first phase of the flood was produced by above five inches of rain and temperatures above freezing in the areas between Berlin and Lewiston. The total of the rain and snow which melted was about nine inches. This produced a flow of 60,000 c.f.s. at Lewiston. The peak required about twenty hours to move from Rumford to Lewiston, a distance of 55 miles or at a rate of 2.7 miles per hour.

During the second storm, melting temperatures prevailed all over the watershed. The average rainfall was 3.7 inches. The water equivalent of the snow which melted was about 6 inches, making the total burden which the river had to carry, rain plus melting snow, about 10 inches. As a consequence the river rose again, this time to an unprecedented height. At Auburn, just below Lewiston, the peak was 135,000 c.f.s. or 41.3 c.s.m.

The magnitude of the flood was much reduced by the 16 billion cubic feet stored in the Rangeley system. At the gaging station near Gorham, N. H., the flow past the gaging station in the period March

*Estimated from the scars on the "freshet oak".

9-22 was 5.23 inches on the watershed above. The quantity stored was 5.06 inches; thus, half the total run-off was stored. At Gulf Island the run-off amounted to about 6.8 inches. The flow stored in the Rangeley System amounted to about 2.5 inches. The damage between Lewiston and the mouth of the river at Brunswick was very heavy, but it would have reached the proportions of a major disaster had it not been for the Rangeley System. The flood peaks on the lower river were distorted by ice jams, particularly by one, formed at the head of Gulf Island Pond, which was about $\frac{1}{2}$ mile wide, $1\frac{1}{4}$ miles long, and extended twenty feet above the water level. When it broke it created a 1.2 foot rise in the pond level. An 80-foot highway truss rode the ice jam buckling on the spillway crest as it went through.

In 1927 the Androscoggin River was on the edge of the storm. At Rumford the peak flow was 46,700 c.f.s., and at Lewiston it was 53,100 c.f.s.

At Lewiston, drainage area 3,257 sq. mi., the records go back to 1850. The largest floods in order of magnitude are as follows:

March 20, 1936	135,000 c.f.s.
March 2, 1896	65,000 c.f.s.
November 5, 1927	60,000 c.f.s.
April 19, 1933	48,500 c.f.s.

Saco River

The Saco River watershed was not affected by either the 1927 or the 1938 storms but the 1936 storm caused the greatest floods known. On the White Mountain portion of the watershed, the precipitation was very heavy, amounting to about 8 inches. Coupled with this was a portion of heavy snow cover. As a result the river rose rapidly. At Conway, N. H., the average 24 hour flow on March 12 and 13 was 10,700 c.f.s., and 18,200 c.f.s., respectively. At Cornish, about 50 miles further down the river, the corresponding figures for March 13, 14, and 15, were 6,000 c.f.s., 9,000 c.f.s., and 12,200 c.f.s. This indicates that a large part of the river run-off went into storage in the river channel, mostly in the natural detention basin above Hiram.

In the second flood the rainfall above Conway was 7.45 inches, resulting in a peak flow of 40,600 c.f.s., equal to 106 c.s.m. on March 19 at Conway from a watershed of 386 square miles. Again the natural detention basin above Hiram was an important factor in reducing

the magnitude of the flows on the lower river. It is estimated that the quantity stored during the flood period amounted to about 12% of the total run-off above Cornish.

The largest floods (average 24 hours) recorded on the Saco River at West Buxton, Maine, are as follows:

March 20, 1936	39,000 c.f.s.
May 2, 1923	27,800 c.f.s.
April 21, 1933	25,600 c.f.s.

Merrimack River

The Merrimack River has been included in the high rainfall areas of all three of the recent great storms, 1927, 1936, and 1938.

In the 1927 flood about 6 inches of precipitation fell in the White Mountain portion of the watershed and over four inches on most of the western area above Concord. This rainfall produced large flood peaks on the mountain tributaries and a major flood on the main river. On the Pemigewasset River at Plymouth a peak of 60,000 c.f.s. was reached, or about 100 c.s.m. On the main river at the gaging station below Lowell, the peak amounted to 76,800 c.f.s., or 16.6 c.s.m. From this figure it is obvious that most of the flood came out of the White Mountain portion of the watershed. Of the smaller mountain tributaries, the highest flow observed was on the Mad River where the flow was 12,000 c.f.s., on 58.4 square miles, or a unit flow of 205 c.s.m.

The March, 1936, flood was characterized by uniformly high flows from all the tributaries, especially high flows on the Pemigewasset and Nashua Rivers, and main river flood peaks which exceed any flood of record by over 50%. The total damage has been estimated at \$35,000,000. Most of this occurred in large cities in the lower valley—Lowell, Lawrence, and Haverhill although several cities on the tributaries suffered severely, notably Fitchburg. At Lowell and Lawrence the public water supplies were flooded, and in the latter city a serious water shortage was narrowly averted.

At the beginning of the flood period, the average water content of the snow above Lawrence was about 4 inches. In the mountains the snow cover was much heavier. The precipitation preceding the first stage of the flood averaged about 3.5 inches over the watershed. This rain and the snow that melted at the same time produced a freshet of about the same size as that of November 1927. Little damage was done during the first flood period.

By March 16, when the rain began again, the rivers were falling

but still high, and the ground was full of water. In the period March 16-19, the average rainfall on the watershed was about 3.3 inches with two areas where the rainfall was over 4.5 inches, one on the upper Pemigewasset and the other on the North Branch of the Nashua River. The rainfall was accompanied by temperatures above freezing which melted practically all the remaining snow. As a result of the second storm, the rivers rose quickly. On the North Branch of the Nashua River, a peak of 16,300 c.f.s. at Leominster, Mass: was reached at 8 p. m. March 18. This peak is equal to 152 c. s. m. and is one of the highest unit flows recorded in the flood. The flows were high all over the watershed. The timing of the flood peaks on the tributaries synchronized to a marked degree with the passage of the flood peak down the river and was an important factor in building up the lower flows. Above the Lowell dam, the flood stage at the peak was 6.4 feet higher than the greatest previous stage, that of the 1852 freshet.

On the main river the record-breaking flows inflicted great damage and there were many spots where the addition of a very few feet of existing water levels would have wiped out entire districts. At Manchester, N. H., the river was prevented from cutting around the east end of the dam into the canal system by a sand bag dam which raised the dam abutments five feet and created a barrier across the railroad tracks. This prevented the river from getting into the canal system, an occurrence which would have created great damage.

At Lowell, Mass., the river cut a shallow channel around the north end of the dam. In the lower portion of the city, some of the more important streets were flooded as were the basements and lower floors of all the mills along the river and a large residential area across the river. At the peak of the flood, the river level near the mouth of the Concord stood higher than the lower canal level, the normal fall from this canal to the river being about 23 feet. At this time only one of the five bridges across the river was passable. At Lowell one of the critically low spots was at the head of the original navigation canal built in 1792. At this point a wooden gate 27 feet wide by 25 feet high, made up of 18-inch white pine timbers, was installed by James B. Francis in 1850 to provide a barrier to be used in a great flood. This gate was closed in the 1852 flood, then raised and not used until 1936 when it was again lowered and again prevented the flood waters from getting into the canal system. The headgate walls and abutments had also been raised after the 1927 flood had indicated the probability of a flood greater than that of 1852. The height of the 1936 flood justified this additional protection.



PLATE II.—PAWTUCKET CANAL HEADGATES AT LOWELL, MASS., 1936, SHOWING THE "FANCES GATE" CLOSED AND ADDITIONAL FLASHBOARD PROTECTION.



PLATE III.—TEMPORARY DAM ACROSS THE BOSTON & MAINE RAILROAD TRACKS AT LOWELL, 1936.

At Lawrence, the possibility of a major disaster due to a break in the canal system was not as serious as at Lowell, but the damage to the industrial and business portion of the city due to back water was very serious. At Haverhill there was also serious damage from the same cause.

In the 1938 flood on the Merrimack River, the run-off was generally high on the western and White Mountain tributaries, with particularly high flows on the upper Contoocook River tributaries flowing out of the Monadnock region. For instance, on Nubanusit Brook at West Peterboro, a unit flow of 90.7 c.s.m. was reached. At Lowell the peak flow was 121,100 c.f.s., or 26.1 c.s.m. On the Pemigewasset River at Franklin, the peak was 54,400 c.f.s. from a drainage area of 1000 square miles, and on the Contoocook River at Penacook the peak was 42,400 c.f.s. from a drainage area of 766 square miles. These figures indicate that something like 80% of the peak was produced from less than half the drainage area.

Arranged in order of magnitude the great floods of the Merrimack River, at Lawrence, in the last ninety-five years, have been as follows:

March 21, 1936	174,000 c.f.s.
September 22, 1938	121,000 c.f.s.
April 23, 1852	108,000 c.f.s.
March 3, 1896	105,000 c.f.s.

Thames River

The flood of November, 1927, was not serious in the Thames River basin. The rainfall amounted to about 5 inches over the drainage area. The eastern tributaries of the Quinebaug River were on the edge of the secondary area of high precipitation in Rhode Island and some high run-off was produced on the Moosup River. At Sterling, an estimated runoff of about 66. c.s.m. took out a portion of a dam. At Jewett City, the peak flow was only 18 c.s.m. on a drainage area of 712 square miles.

The March, 1936, flood was very severe on the smaller streams which make up the Thames River, notably the Quinebaug, the Shetucket, and the Willimantic Rivers. The average rainfall during the storm of March 11-12 was 2.65 inches. This rainfall took off all the snow cover the estimated water content of which was about 2.3 inches. The resulting flows on some of the tributaries were over 50 c.s.m. On the western slopes, these flows were higher than those of the week following. In the second storm, Southbridge was the center

of the area of greatest rainfall. Here the rainfall on March 17 was 1.27 inches and 3.89 inches on March 18. The resulting flows were very high. On the smaller tributaries many flows were recorded over 60 c.s.m. Of these, a peak of 14,200 c.f.s. from 169 square miles on the Natchaug River at Willimantic was the most notable.

In the September, 1938, flood the area of maximum rainfall extended over the greater part of the Thames River watershed, resulting in record breaking flood flows. On most of the tributaries, because great floods have been rare, the flood channels had been encroached upon so that the extraordinary high flows did great damage to structures in the river valleys and caused some loss of life. At Southbridge, Mass., the total rainfall, September 17-22 was 13.5 inches, of which 6.9 inches fell September 20. At Stamford, Conn., the total from the storm was 14.11 inches, of which 6.21 inches fell September 20. On the Quinebaug River watershed the average rainfall was 13.25 inches. The area of this rainfall did not extend to the eastern portion of the Thames River Watershed.

The excessive rainfall on the western slopes produced flood peaks which surpassed those of 1936 and were comparable to the 1927 floods in Vermont. On the Natchaug River at Willimantic, the flow was over twice as great as in 1936, being 189 c.s.m. On several of the smaller streams in Connecticut, flows about as great as this were observed. Nowhere in New England was the relative damage greater than on the Quinebaug River. Through Southbridge, all five dams were badly damaged. The flood peak at Quinebaug, Conn., was 90 c.s.m. Previous to 1936, the greatest flood in this watershed resulted from the storm of March 25-26, 1876. It was in this flood that the dam at Baltic, Conn., went out; at Greenville, Conn., the flow from 1260 square miles was 47,600 c.f.s. In September, 1938, the peak at Baltic was 77,700 c.f.s., or 61.7 c.s.m., in other words, it was over 50% greater than any flood of record.

Connecticut River

The watershed of the Connecticut River was in the areas of maximum run-off in the 1927, 1936, and 1938 floods.

In the November, 1927, floods, some of the highest flows ever observed in New England occurred on the Connecticut River tributaries rising in the Green Mountains. The greatest rainfall measured during the November 3-4 storm was at Somerset, Vermont, where the total precipitation in two days was 9.65 inches, of which 8.66 inches

occurred in one 24-hour period. The area included in the 7 inches isohyetal line extended over the western tributaries as far north as the White River, and over a considerable portion of this area the rainfall was over nine inches. In this area, the flood peaks were very great. On the White River at West Hartford a flood peak of 120,000 c.f.s. from a drainage area of 690 square miles occurred. This peak, 174 c.s.m., even after the 1936 and 1938 floods, still stands as the highest flow in New England for drainage areas of comparable size.

On the western tributaries from the White River to the Westfield River, the flows were generally 50 to 100% higher than previously recorded flows in these localities. The same was true for the streams rising in the White Mountains. Further north, and from all the eastern tributaries south of the mountains, the run-off, while great, was not of the same magnitude. On the Connecticut River itself, most of the peak flow came from the White River. For instance, at Holyoke, the peak was 183,000 c.f.s. from 8284 square miles as compared to the 120,000 c.f.s. peak which came from the White River.

The 1936 flood on the Connecticut River itself was produced by generally high flows over the entire watershed. In 1927 the flows from Central Vermont streams were greater than in 1936, and in 1938 from streams in Massachusetts and Connecticut were generally higher, but in terms of total flood run-off, and main river flood peaks, the 1936 flood was the largest in the history of the river.

At the beginning of March, the water content of the snow on the

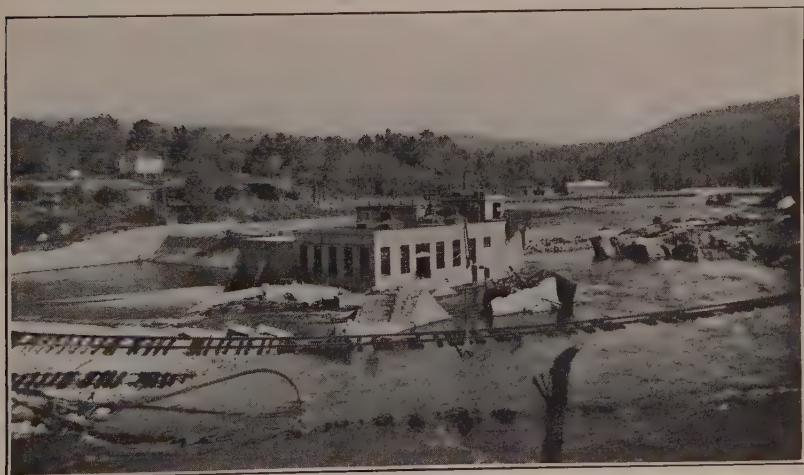


PLATE IV.—POWER PLANT AND RAILROAD AT WENDELL, MASS., ON THE MILLERS RIVER.

Connecticut River watershed varied from 3 inches in Connecticut to 8 to 10 inches in Green and White Mountains. On March 11, and 12, heavy rains accompanied by temperatures above freezing, below White River, melted most of the snow cover in this area and created a freshet somewhat greater than most spring freshets. At Holyoke, the peak was 100,000 c.f.s., equal to 12 c.s.m. Flows greater than this have been observed 15 times since 1850. The ice as far north as Vermont went out with this flood peak. A serious ice jam formed above Holyoke near the Ox Bow on March 13 and held until the evening of March 15, completely blocking the channel. As a result, the river overflowed the meadow on the east side and cut a new channel to the downstream end of the jam. When the ice jam finally broke, it moved downstream at a rate of about $6\frac{1}{2}$ miles per hour passing over the Holyoke dam in $9\frac{1}{2}$ feet of water. Later it was found that about 1000 feet of the granite crest of the Holyoke dam had been taken off to a depth of 5 feet.

By March 16, the peak was over but most of the streams were at the "bank full" stage. Rain began to fall again and continued through March 19, resulting in an average rainfall of about 4.5 inches and melting practically all the remaining snow. The combination of rainfall and melting snow quickly produced new and greater flood peaks.



PLATE V.—INTERIOR OF THE NO. 4 POWER PLANT AT SHELBURNE FALLS, ON THE DEERFIELD RIVER, AFTER THE 1938 FLOOD.

On most of the tributaries, the peaks were reached on March 18 or early on March 19. In general the tributary floods were greater than any recorded up to that time except in the vicinity of the White River. The highest unit flows occurred in the Western Massachusetts streams in the secondary area of high precipitation. With no release from Hariman reservoir, the peak on the Deerfield River from the 316 square miles below, was 166 c.s.m. The Westfield River at Westfield reaches a peak flow of 48,200 c.f.s., equal to 97 c.s.m.

A study of the hydrographs of the main river stations indicates that the upper portion of the watershed above Fifteen-Mile Falls did not contribute its proportionate share of the flood peaks on the lower river. But below South Newbury, the time of the tributary peaks synchronized with the passage of the flood down the main river and was an important factor in producing the tremendous main river flood stages. The fact that the lower river ice went out during the earlier flood, considerably mitigated the damage to river structures. The Sunderland bridge was destroyed, as were many above this point, including the wooden covered bridge at Montague and the famous suspension bridge at Brattleboro.

The storm of September, 1938, produced flows of extraordinary magnitude on the central and southern portions of the Connecticut River watershed. North of White River Junction, the flood peak was of the magnitude of the freshet expected about every ten years, yet the lower tributary flows were great enough to produce the second highest stage ever recorded at Hartford. The heaviest precipitation which was observed during the entire storm occurred a few miles west of the eastern limit of the Connecticut River watershed. At Barre, Mass., the total rainfall September 17 to 22, inclusive, was 17.03 inches. At Camp Buck, near Middletown, Connecticut, 17.07 inches fell during the storm. On the entire eastern portion of the watershed as far north as the New Hampshire line, the average precipitation was over 10 inches, and on some portions it exceeded 12 inches. On the western slopes of the Connecticut River watershed, the rainfall, while heavy, was not as great as in the eastern part. There were several stations where a storm rainfall of over 11 inches was reported and many of over 10 inches. Considering the watershed as a whole, the average rainfall above South Newbury was 4.2 inches, and for the portion between South Newbury and Hartford, the average was 8.8 inches.

Unfortunately no recording rain gauges were located in the areas

of highest precipitation. However, from records obtained in adjacent areas of high precipitation, it is evident that there was precipitation of great intensity. At Hoosac Tunnel, the total storm rainfall was 9.91 inches of which 2 inches of rainfall occurred between 2 and 4 p.m. Further south, at Hartland Hollow, Conn., the total storm rainfall was 11.42 inches of which 1.9 inches of rain fell between 4 and 5 p.m. September 21. At Barre, Mass., 11.83 inches of rain fell in the 24 hours ending in the morning of September 20.

The total run-offs and the flood peaks on the smaller rivers which were produced in Massachusetts and Connecticut, exceeded by 50% to 100% the highest flows previously recorded. On drainage areas of



PLATE VI.—THE 1938 FLOOD ON THE CHICOPEE RIVER AT CHICOPEE FALLS, MASS...

less than 50 square miles flows over 500 c.s.m. were observed. These all occurred on the steep narrow valleys of the Deerfield River watershed. In these valleys the roads follow the streams, and after the flood virtually all the roads were rendered impassable and the bridges were washed out. On the Deerfield River between Harriman Reservoir and Charlemont, a peak of 56,300 c.f.s. was produced from the 178 square miles below Harriman. An equally great run-off was impounded in the reservoir and substantially reduced the down-river peak.

On eastern tributaries, the magnitude of the floods is shown by the fact that entire river valleys were devastated. On the Millers

River virtually all the dams were damaged generally by the abutment being overtopped. The Wendell hydro-electric station was so badly damaged that it was not rebuilt. At the Erving gauging station, the flow was 29,000 c.f.s, equal to 78.4 c.s.m., which is 50% greater than the previous high, the 1936 flood.

On the adjoining watershed, the Chicopee, the total damage was large and would have been greater had it not been for the run-off stored behind the baffle dam which is part of the Quabbin Reservoir development. Because of this the Swift River peak was less than that



PLATE VII.—HEAVY ICE APPROACHING THE CREST OF THE SPILLWAY OF THE VERNON DAM, 1936.

in 1936, but on the other two major tributaries, the flood peaks were about twice as great as in 1936. On the Ware River all the dams were severely damaged. At all the dams on the Chicopee River the maximum water level was above the tops of the abutments by about $1\frac{1}{2}$ to 2 ft. Further south, in Connecticut, the floods were very heavy on both sides of the main river. On that part of the Hockanum River tributary to Shenipsit Lake, the average rainfall was 14.8 inches and the resulting run-off 9.9 inches. This is the greatest total run-off measured on any stream during the storm.

The largest floods on the Connecticut River during the last 100 years are shown in the order of their magnitude on the following table:

	PEAK FLOW AT THOMPSONVILLE	HARTFORD GAUGE HT.
Mar. 21, 1936	282,000 c.f.s.	37.6 ft.
Sept. 22, 1938	236,000 "	35.4 "
May 1, 1854	198,000 "	29.8 "
Nov. 6, 1927	190,000 "	29.0 "
Apr. 21, 1862	183,000 "	28.7 "
Apr. 23, 1869	160,000 "	26.7 "

Housatonic River

On the lower Housatonic River, the floods in recent years, while large, were surpassed by the flood which resulted from the storm of October, 1869.

In the 1927 flood, the Housatonic River lay south on the area of highest rainfall. Six to seven inches fell on the upper watershed, diminishing to four inches near the coast. Near Dalton, Mass., a peak flow of 108 c.s.m. was recorded.

In March, 1936, the greatest flows occurred during the March 11-13 storm. In this storm the average rainfall on the watershed was 2.6 inches with individual stations reporting up to 4.5 inches. Practically all the snow cover, having an average water content of 3.8 inches, melted with this rainfall. The ice went out with this freshet and resulted in many ice jams and considerable damage. At Stevenson, Conn., the maximum flow was 69,500 c.f.s. Some of this peak was caused by ice jams upstream letting go. In the second phase of the storm, the rainfall was about the same as during the earlier one but with the snow gone, the flood peaks were generally less.

In the September, 1938, flood, the Housatonic River was west of the heaviest rainfall. The watershed was subjected to about 10 inches of precipitation in the period September 17-21. The resulting run-off was generally higher than that in 1936 and on many tributaries the flood peaks were greater than any of record.

Western Vermont Streams

In the 1927 flood, the Vermont streams tributary to Lake Champlain were in the area of highest precipitation. The rainfall varied from 9 inches on the headwaters to 4 inches near Lake Champlain. Most of this rain took place in about 24 hours. The river valleys in this area are narrow and steep so that flood peaks of great intensity built up very quickly. The resulting damage to towns in the river valleys, highways and railroads was very large. In the Winooski River valley, where the damage was worst, 55 lives were lost and the

damage has been estimated at \$13,500,000. On the Winooski River near Essex Junction, a peak of 113,000 c.f.s. was observed, equal to 105 c.s.m. This flow still stands as one of the outstanding flood peaks in New England flood history. On the tributaries of the Winooski River, a peak of 248 c.s.m. occurred on the North Branch at Wrightsville, and one of 349 c.s.m. on the Jail Branch at East Barre. On the other Vermont streams, Otter Creek, the Lamoille, and the Missisquoi Rivers, the floods, while the greatest in history, were not as large as on the Winooski River.

In the 1936 flood, the Vermont rivers were higher than during the usual spring floods, but did not approach the 1927 stages. On March 1, the water equivalent of the snow on the ground varied from about 7 inches in the Green Mountains to 2 inches near Lake Champlain. The rainfall March 9-13 was nearly 2 inches. It melted about half the snow cover, and produced a flood of moderate proportions. The peak on the Winooski River near Essex Junction was about 26 c.s.m. and of about the same magnitude on the Lamoille River. Preceding the second phase of the flood the rainfall was about 2 inches. This melted the greater part of the remaining snow cover and produced flood flows of considerable magnitude. On the Winooski River near Essex Junction, the peak flow was 45,300 c.f.s. equal to 42 c.s.m. The flood stages on the Winooski were somewhat reduced by the water stored in two newly constructed reservoirs on North and Jail Branches, whose combined drainage area is 102 square miles, 24% of the drainage area at Montpelier, and 9.5% of the drainage area at Essex Junction. In the period March 9 to 23, 1100 million cubic feet was stored in the reservoirs amounting to 12% and 4% of the total runoff at Montpelier and Essex Junction respectively.

In September 1938 the Vermont streams tributary to Lake Champlain lay north and west of the direct path of the storm. The southern portion of this area, included in the headwaters of Otter Creek, were on the edge of the area of high precipitation which produced the extraordinary high flows on the Connecticut River tributaries rising in the southern Green Mountains. In this area, the rainfall occurred in the period between 4:00 a.m. September 19 and midnight September 21. The highest rainfall observed during the storm on the Vermont area tributary to Lake Champlain was at Goshen, where the total was 6.32 inches. In general the average rainfall diminished from about 6 inches on the headwaters of Otter Creek to above 3 inches on the most northerly watersheds.

The 1938 flows in this area did not approach the 1927 flows, but the run-off was high and some sizable flood peaks were observed. On Otter Creek at Center Rutland a peak of 13,700 c.f.s. was obtained from a drainage area of 307 square miles. Further north the run-off was less. On the Lamoille River at Fairfax Falls, the flow per square mile of drainage area was 34.3 c.s.m. and the flood peaks on the larger streams were of about this magnitude. The 1938 flood afforded a further demonstration of the operation of the three detention reservoirs on the headwaters of the Winooski River. At Waterbury Reservoir the total rainfall was 2.6 inches, of which 1.9 inches was detained. The maximum outflow was 694 c.f.s. or 6.4 c.s.m.; it is estimated that, without the detention reservoir, the flood peak would have been 3900 c.f.s., or 35.8 c.s.m., the reduction in the size of the flood peak being 85%. At Wrightville and East Barre reservoirs, the reduction produced in the flood peak was 69% and 65% respectively.

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CHAPTER III

Storm Rainfall

The maximum flood producing storms in New England for which adequate records are available for comparison are those of October 3-4, 1869; July 12-14, 1897; November 2-6, 1927, which caused the Vermont flood; September 16-17, 1932, a great storm which produced no serious floods; the two storms which occurred within the period March 9-22, 1936, which resulted in the 1936 flood; and the storms of September 17-21, 1938, which preceded the hurricane and caused disastrous floods in certain sections. The total area upon which precipitation occurred in these storms varied from 80,000 to 350,000 square miles. Since even the largest rivers of New England have drainage areas much less than the total areas covered by the storms, consideration of the intensity, duration and depth of rainfall over relatively small areas becomes critical. The areas of the watersheds of the larger rivers in New England shown on Fig. 1 are as follows:

<i>Maine</i>	
Penobscot River	7,760
Kennebec River	5,550
<i>Maine and New Hampshire</i>	
Androscoggin River	3,430
Saco River	1,677
<i>New Hampshire and Massachusetts</i>	
Merrimack River	5,006
<i>New Hampshire, Vermont, Massachusetts and Connecticut</i>	
Connecticut River	11,236
<i>Massachusetts and Connecticut</i>	
Housatonic River	1,949
Thames River	1,471

The average rainfall in these storms over 6,000 square miles which is comparable to the watershed areas of the four largest New England rivers for the largest storms of record was as follows:

Storm	Average Rainfall*
	6000 Square Miles Inches
October 3-4, 1869	7.6
July 12-14, 1897	6.9

*Data from Water-Supply Paper 867.

Storm	Rainfall—Inches
November 2-6, 1927	7.7
September 16-17, 1932	7.8
March 9-22, 1936	12.25**
March 9-13	5.45
March 16-19	6.8
Sept. 17-21, 1938	12.3

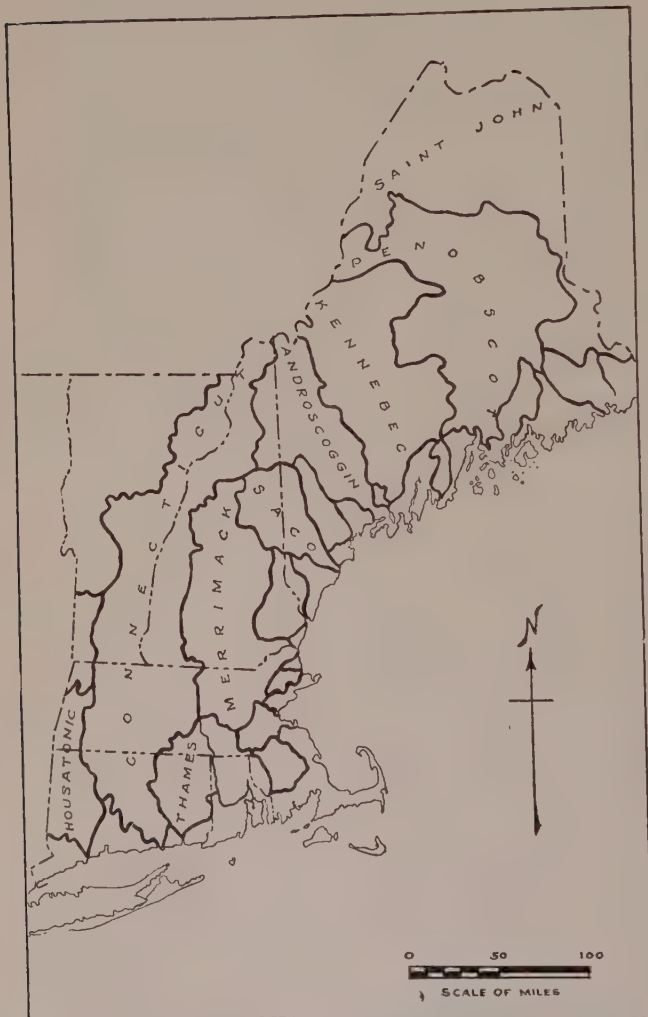


FIG. 1.—DRAINAGE BASINS OF THE NEW ENGLAND RIVERS IN UNITED STATES.*

**Total of three storms.

*Taken from U. S. Geol. Survey Water Supply paper 798.

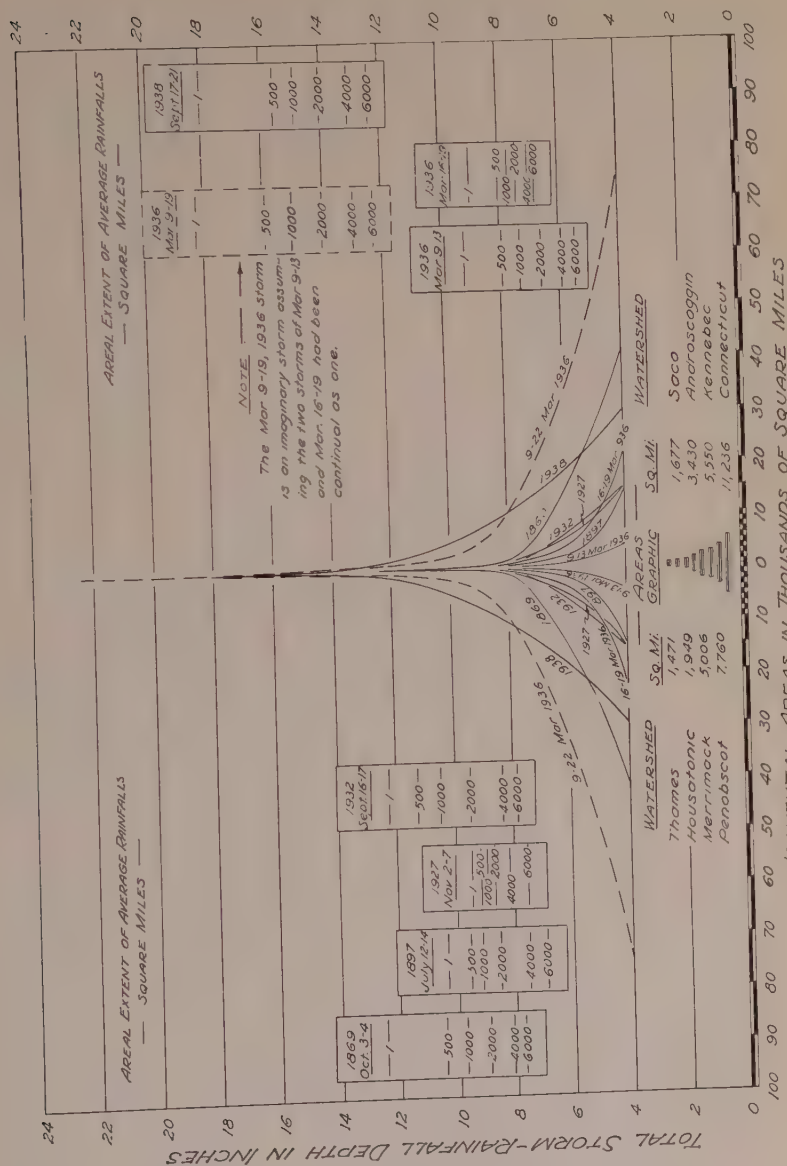


FIG. 2.—DISTRIBUTION OF STORM RAINFALLS.

Fig. 2 gives a visual comparison of the character and scope of these major storms.

While it may be appreciated that storms of long duration may be critical on the larger streams, intense storms of shorter duration become critical on the small drainage areas. Fig. 3 shows the areas

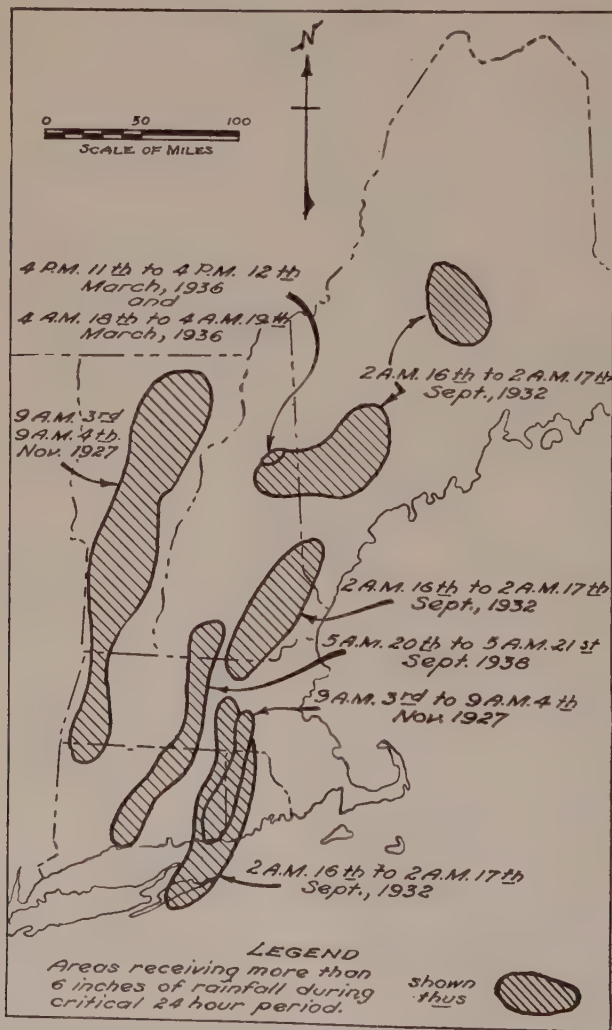


FIG. 3.—LOCATION OF MAJOR STORMS OF RECORD IN NEW ENGLAND REGION.*

*Taken from Ompompanoosuc Basin Report of U. S. Weather Bureau, March 18, 1940.

receiving more than six inches of rainfall during a critical period of 24 hours during the major storms of record in the northeastern region.

STORM OF NOVEMBER 2-6, 1927¹

This storm was characterized by a cold front in an elongated pressure trough which moved relatively slowly eastward during November 1-2, finally becoming a quasi-stationary front from Georgia to Maine by the morning of November 3.

The warm air mass to the east of the stationary front was quite moist and unstable as evidenced by the existence of a tropical storm and by the fact that cyclone formation took place so rapidly. However, it should be emphasized that the tropical storm itself never merged with the pressure trough and that the quantities of water vapor in the moist current could have been much greater if they had merged.

During the day of November 3, 1927, two small cyclones developed and moved quite rapidly northward along the quasi-stationary front through Vermont. The precipitation as a whole was produced by the gradual lifting of warm moist air as it moved over cooler and more stable air. The concentration and intensification of rainfall was caused by the general convergence associated with the pressure trough and the local convergence accompanying the passage of the small intense cyclones.

STORM OF SEPTEMBER 16-17, 1932¹

While this storm did not result in disastrous floods because of the lack of other favorable flood producing conditions, the heavy precipitation occurred in these storms varied from 80,000 to 350,000 origin in the southwest Gulf of Mexico on September 9, and which by the morning of September 16 centered about 150 miles east of Norfolk, Virginia. A disturbance over Ontario had moved eastward so that its trough extended southward through eastern New York toward the tropical disturbance. Strong convergent flow in the trough north of the tropical disturbance resulted in vertical divergence, decreasing stability, and heavy rainfall as far north as northern Maine.

¹Abstract from "A Report of the Maximum Possible Precipitation Over the Ompompanoosuc Basin above Union Village, Vermont." Weather Bureau, U. S. Department of Commerce.

STORM OF MARCH 9-22, 1936¹

This storm is usually considered in three periods, viz. March 9-13, March 16-19, and March 20-22. During the first period a deep cold cyclone formed over the Great Lakes region accompanied by a strong gradient from north to south over the Middle Atlantic States in the upper levels of the troposphere. An up-glide motion of warm moist air from south to north over New England accompanied by very intense circulation aloft resulted in the precipitation from March 9-13 inclusive. During the period from March 16-19, as a result of a rapid southward thrust of cold air from Minnesota to Georgia, a cyclonic disturbance developed and moved northward from Virginia along the Atlantic coast producing a period of heavy rainfall. Active convergence and warm front lifting in the pressure trough north of the center caused moderate to heavy precipitation from moist tropical air moving northwestward. Stagnation of this pressure trough maintained a strong persistent flow of warm tropical air which aided in the melting of snow already ripened by rainfall and warm air during the preceding storm. The terminal period of this storm from March 20-22 was marked by the formation of a cold cyclone in the upper levels over North Dakota, and its rapid push southward to Alabama, followed by the formation of a cyclone over Indiana, with secondary development along the Atlantic coast which moved northward causing moderate rains. The rate of precipitation may be considered as a function of the amount of precipitable water available and of the rate at which this moisture is transported northward.

STORM OF SEPTEMBER 17-21, 1938¹

The heaviest rainfall during this storm occurred just prior to the New England hurricane. A deep cold cyclonic disturbance over Lake Michigan was inducing a pronounced northward flow of warm moist air over New England. A typical inverted "V" pressure trough with its quasi-stationary front developed over central Connecticut and Massachusetts. The circulation which caused the front to stagnate also caused the hurricane to move through the frontal zone. The high intensities of rainfall were caused by strong wind velocities in the upper atmospheric levels which also caused the hurricane to move rapidly through New England.

¹Abstract from "A Report of the Maximum Possible Precipitation Over the Ompompanoosuc Basin above Union Village, Vermont." Weather Bureau, U. S. Department of Commerce.

MAXIMUM POSSIBLE PRECIPITATION¹

Studies have been made by the U. S. Weather Bureau of the U. S. Department of Commerce with regard to the design of flood prevention works at Union Village, Vermont, in the Ompompanoosuc Basin. The report relative to these studies contains considerable data as to intensity of past storms over areas up to 1,000 square miles. Estimates were made of the maximum possible rainfall on similar areas, on the basis that the average intensity of rainfall over a large area depends upon the quantity of moisture available, and the rate at which moisture-bearing air can be brought into the rain zone. Over large areas the up-glide phenomenon predominates and over smaller areas the convergence theory more nearly applies. In arriving at conclusions as to the maximum possible rainfall, the Weather Bureau has considered the amount of moisture which might have been precipitated under the most favorable meteorological conditions of maximum dew points. In other words, it can be statistically determined what surface dew point can be considered a maximum during a rainy period, and the depth of precipitable water for that maximum dew point can be computed. This computed depth can be compared to the observed or estimated depth of precipitable water during a major storm period and the actual storm values can be extrapolated proportionately. In general, these studies concluded that the total precipitation rates could have been from 15 to 30 per cent larger in the four recent major storms.

Since there are many small streams of New England to which these conclusions may apply, there are here reproduced two diagrams from this report, Fig. 4 showing the enveloping duration-depth curves of maximum actual rainfall for record storms in the New England region, and Fig. 5 showing the enveloping duration-depth curves of maximum possible rainfall for selected basins in the New England region. These diagrams deal with watersheds up to 1,000 square miles.

There are also included diagrams, Fig. 6, showing the average depth in inches to be expected in progressive six-hour intervals up to 48 hours for watersheds from 100 to 1,000 square miles on selected basins in the New England region and Fig. 7, showing arrangements of maximum possible rainfall for such drainage areas. The above studies of the U. S. Weather Bureau afford a rational approach to the problem of determining the maximum possible rainfall which might

¹Abstract from "A Report of the Maximum Possible Precipitation Over the Ompompanoosuc Basin above Union Village, Vermont." Weather Bureau, U. S. Department of Commerce.

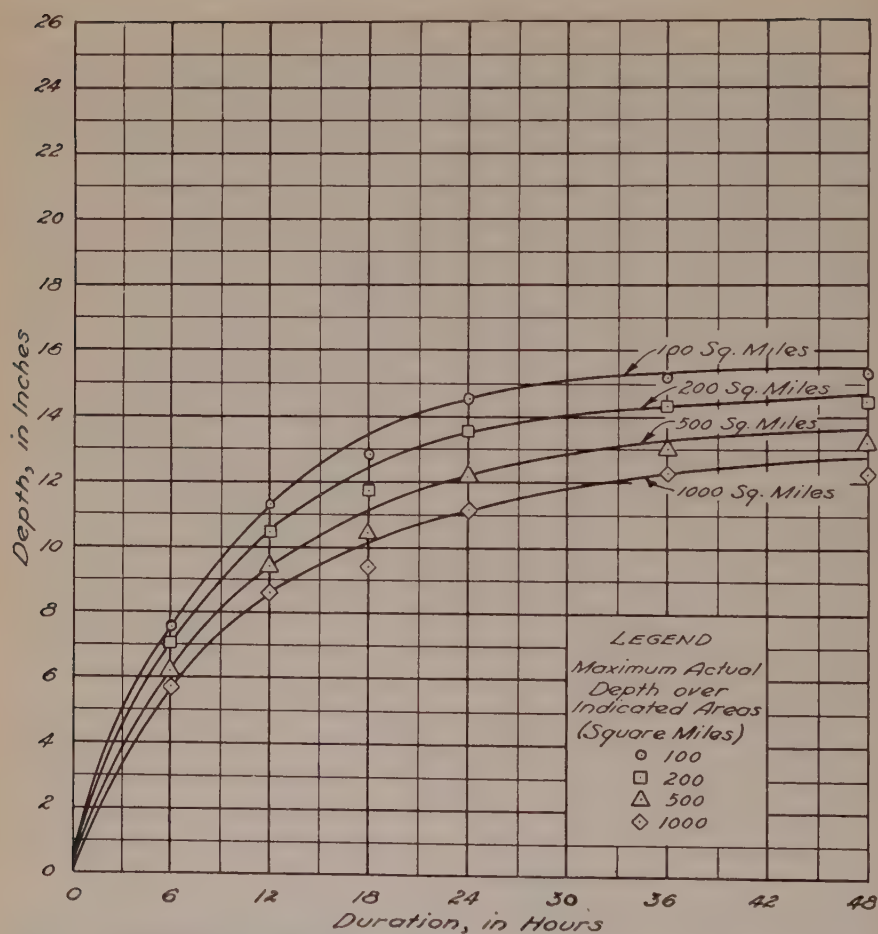


FIG. 4.—ENVELOPING DURATION-DEPTH CURVES OF MAXIMUM ACTUAL RAINFALL FROM RECORD STORMS IN THE NEW ENGLAND REGION.*

occur over relatively small areas in relatively short periods of time. The research of the Miami Conservancy District of Ohio in the matter of floods of certain European rivers where records are available in some instances for several thousand years led to the conclusion that floods 25 per cent in excess of these experienced in the Miami district might be expected to occur in that region.

In arriving at a conclusion as to how much greater rainfall might be expected to occur over large areas in New England, it is pertinent

*Taken from Ompompanoosuc Basin Report of U. S. Weather Bureau, March 18, 1940.

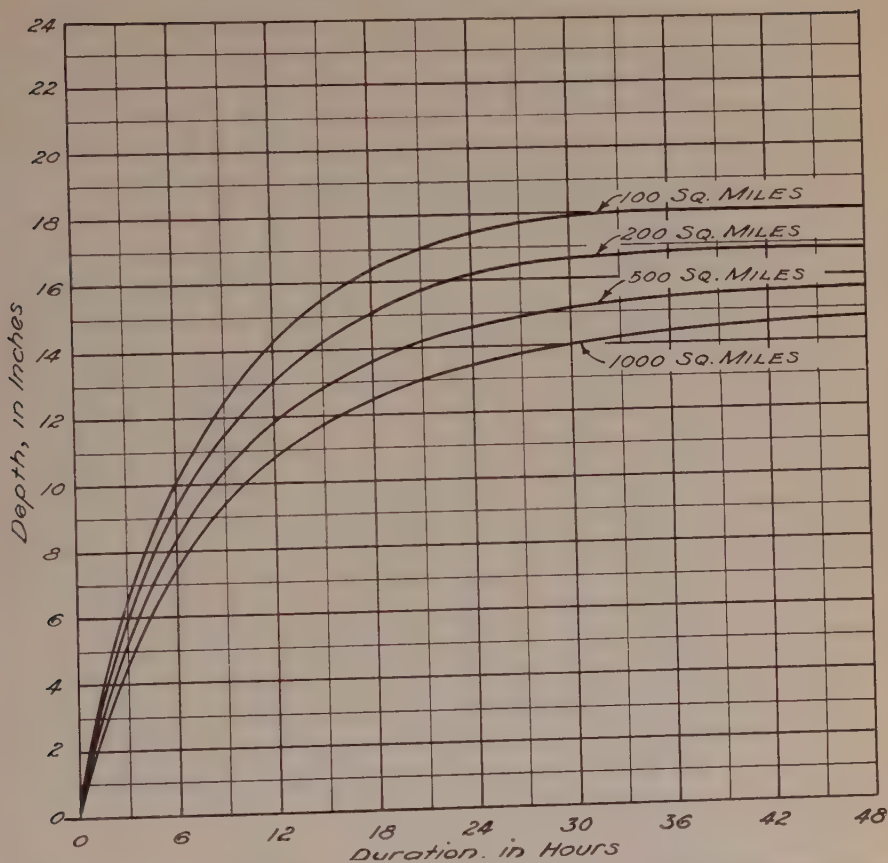


FIG. 5.—ENVELOPING DURATION-DEPTH CURVES OF MAXIMUM POSSIBLE RAINFALL OVER SELECTED BASINS IN THE NEW ENGLAND REGION.*

to review the November 2-7, 1927, storms where a mergence of a tropical storm with the general up-glide of warm air in the low pressure trough could have resulted in much greater rainfall. It is also interesting to note that the total rainfall of the two storm periods of March 9-13 and March 16-19, 1936, were approximately equal, over an area of 6,000 square miles, to that over a similar area during the period from September 17-21, 1938.

The rainfall for the two periods in the 1936 storm probably could not have occurred simultaneously over the same area. The rainfall

*Taken from Ompompanoosuc Basin Report of U. S. Weather Bureau, March 18, 1940.

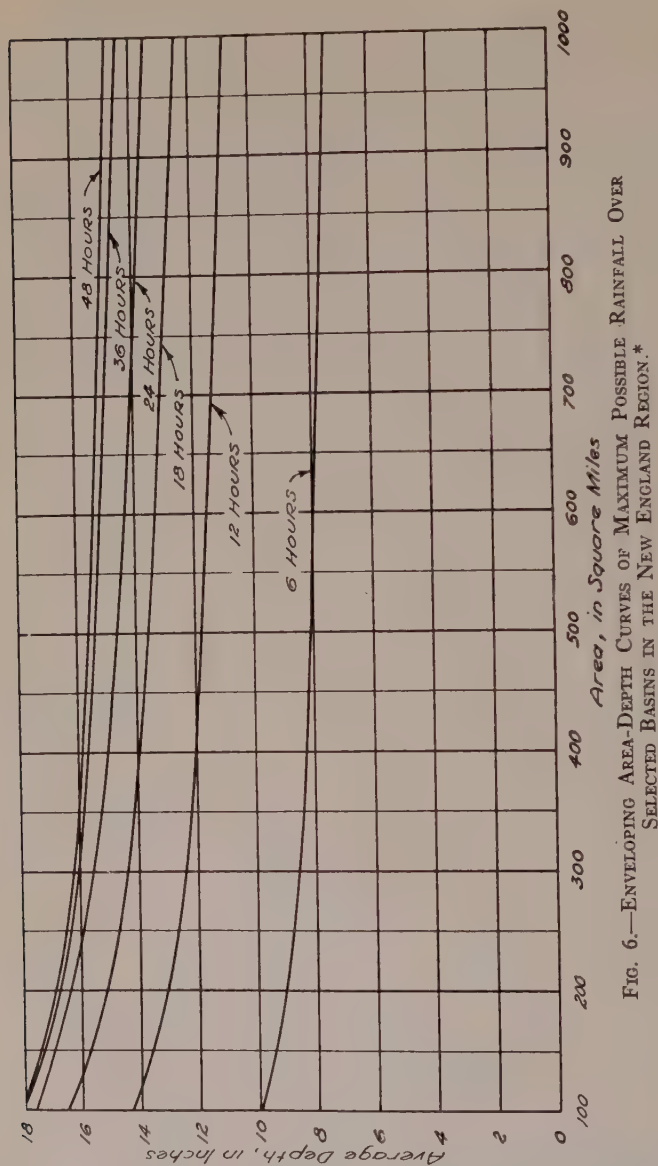


FIG. 6.—ENVELOPING AREA-DEPTH CURVES OF MAXIMUM POSSIBLE RAINFALL OVER SELECTED BASINS IN THE NEW ENGLAND REGION.*

*Taken from Ompompanoosuc Basin Report of U. S. Weather Bureau, March 18, 1940.

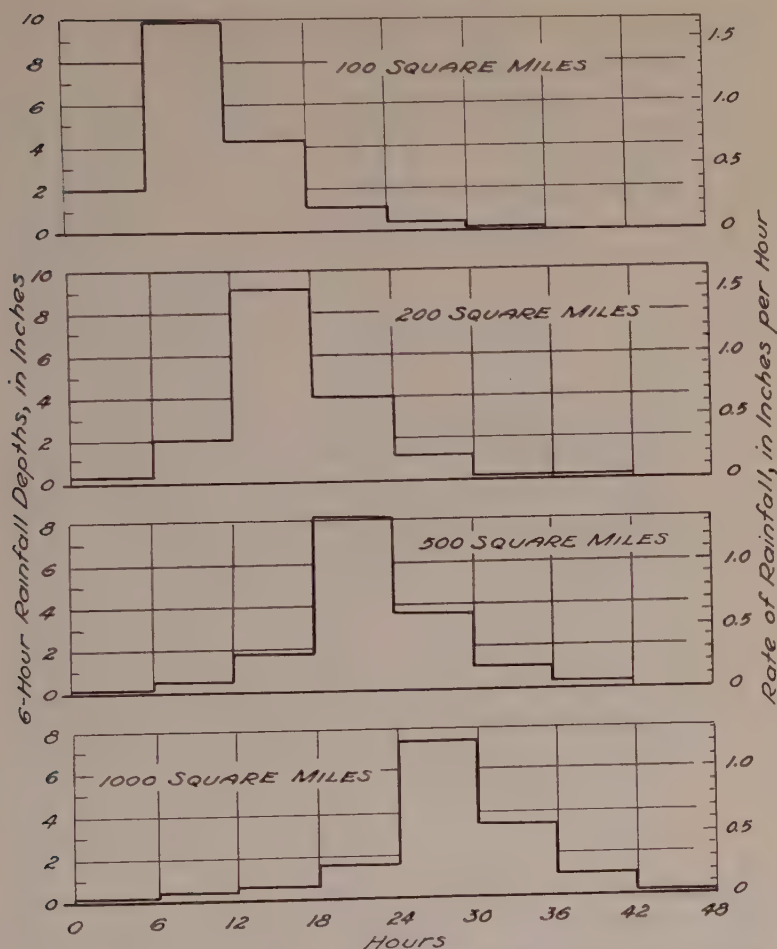


FIG. 7.—ARRANGEMENT OF MAXIMUM POSSIBLE RAINFALL OVER DRAINAGE AREAS OF VARIOUS SIZES.*

conditions accompanying the 1936 and 1938 floods are described in detail in the two following sections.

FLOOD OF MARCH, 1936

The 1936 flood was caused by a coincidence of several factors favorable to flood conditions, none of which were especially unusual when taken alone. In general, these conditions included a cold win-

*Taken from Ompompanoosuc Basin Report of U. S. Weather Bureau, March 18, 1940.

ter, considerable accumulation of snow on the ground, ground frozen with a considerable penetration of frost, and heavy rainfall accompanied by relatively high temperatures immediately preceding and during the storm. If each of the meteorologic phenomenon over the area as a whole is considered individually, no departures from the normal that are sufficient to have caused so unusual a flood are disclosed. There have been colder winters with more snow, individual storms with precipitation exceeding that of either of the March storms, and higher temperatures in the early spring. However, consideration of the magnitude and favorable timing of the events as a whole disclosed extremely unusual conditions. It is also evident that with only slightly different timing or combination of events and conditions the flood run-off in any areas might have been much greater. The precipitation in the months of December, January and February preceding the flood of March 1936 are shown in Table 1. This table shows

TABLE 1.—MONTHLY PRECIPITATION AND DEPARTURES FROM NORMAL, IN INCHES, IN THE NEW ENGLAND STATES, DECEMBER 1935 TO FEBRUARY 1936.

State	December 1935	December Departure	January 1936	January Departure	February 1936	February Departure	December to February 1935-6	Departure
Maine	1.91	—1.33	6.40	+2.87	2.75	—0.24	11.06	+1.30
New Hampshire	1.25	—1.70	6.07	+3.06	2.31	— .36	9.63	+1.00
Vermont	1.20	—1.43	4.83	+2.05	2.05	— .41	8.08	+0.21
Massachusetts	1.25	—2.28	6.78	+3.06	2.95	— .53	10.98	—0.25
Rhode Island	1.16	—2.65	6.96	+2.91	4.06	+ .38	12.18	+0.64
Connecticut	1.05	—2.68	7.01	+3.15	2.70	— .90	10.76	—0.43

that the antecedent precipitation throughout the New England States was below normal during December and February, and considerably above normal during January. The totals for the three months were slightly above normal.

Snow

For New England as a whole there was slightly more snowfall than normal during the months of December, January and February. The monthly totals and departures from normal as compiled from records of the United States Weather Bureau are shown in Table 2.

Abnormality with respect to the snowfall was apparently shown in the extent to which it accumulated on the ground during the winter on account of long cold periods rather than in the relatively small

TABLE 2.—MONTHLY SNOWFALL, IN INCHES, IN NEW ENGLAND, DECEMBER 1935 TO FEBRUARY 1936.

State	December	January	February	Total
Maine	14.3	36.1	19.7	70.1
New Hampshire	9.6	35.7	20.0	65.3
Vermont	7.7	29.3	18.1	55.1
Massachusetts	3.1	18.0	14.9	36.0
Rhode Island	4.4	7.7	7.6	19.7
Connecticut	4.4	17.4	13.4	35.2
Average for New England	7.2	25.5	16.7	49.4
Normal average	11.6	15.6	17.0	43.6
Departure from normal	-4.4	+9.9	-.3	+5.8

excess in the total amount above normal. On March 9 all of New England was covered with snow, except a narrow coastal area from Boston southward nearly to New Haven. On Fig. 8 is shown the estimated water content of the snow on the ground March 9, 1936, which corresponds to total snow depletion in areas where all of the snow disappeared by March 22, and, in areas where snow remained on the ground after the floods, represent a figure greater than the depletion during the floods. Considerable amounts of snow remained on the ground on March 22 in the headwater areas of the Connecticut, Merrimack, Androscoggin, Saco, Kennebec and Penobscot Rivers. The rainfall and run-off studies show the important part played by run-off from melting snow in the flood situation.

Frost in the Ground

As the temperatures were, in general, below normal throughout New England during the greater part of December, January and February and remained so until about March 9, it would seem that, other things being equal, conditions for producing frozen ground prior to the floods were more than normally severe. The protection from freezing that the ground may have derived from the snow cover was so variable, however, that general conclusions regarding departures from normal may be meaningless. From such frost observations as are available, the general conclusion may be drawn that where there is a heavy snow cover throughout the winter there will be little frost, but that in areas with light snow cover frost will be present to a large degree. So far as the presence of frost affects infiltration rates and run-off, consideration should be given to the possibility that in

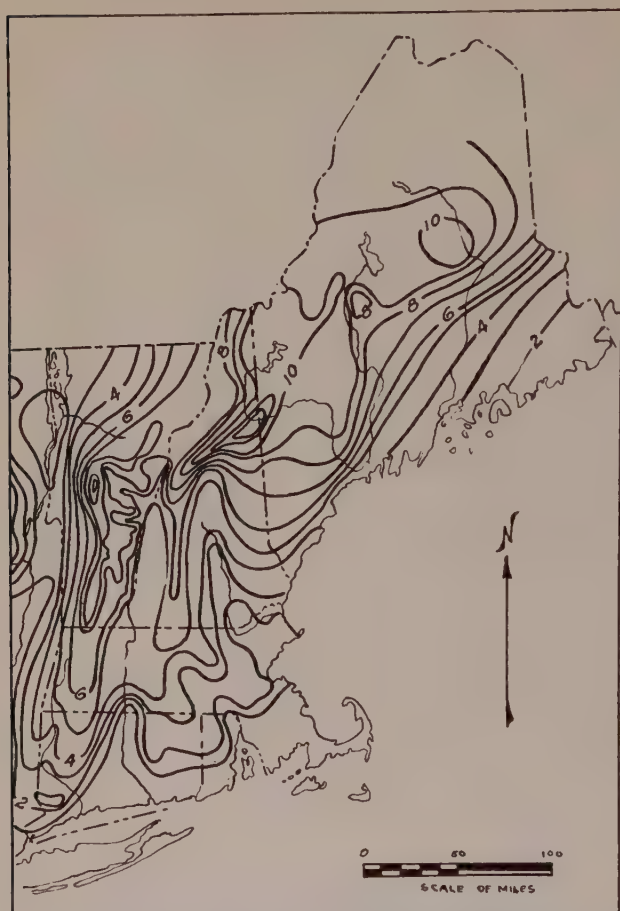


FIG. 8.—MAP OF NEW ENGLAND SHOWING THE DEPTH, IN INCHES, OF THE WATER CONTENT OF SNOW ON THE GROUND, MARCH 9, 1940.*

some areas, at least, thin impervious stratum of earth and frozen moistures may have effectively retarded infiltration and increased surface run-off.

Conditions Immediately Preceding the Flood Temperature

Temperature played a very important part in the development of the floods of March 1936. First, beginning with December and continuing through February, temperatures, in general, were below nor-

*Taken from U. S. Geol. Survey Water Supply paper 798.

mal; second, there were long periods during which there was little if any thawing. At the northern stations the maximum daily temperature rarely exceeded 40° and the minimum temperature rarely exceeded 32° F. during the entire period December 1 to March 9. At the southern stations there was some thawing during the first half of January, followed by six weeks of continuously cold weather, broken only by occasional melting in the middle of the day. These temperature conditions indicate first, that over much of northern New England, except for the evaporation from the snow and an indeterminate amount of thawing next to the ground surface, a considerable part of the precipitation that fell in the form of snow during the period from December 1 to March 9 was on the surface of the ground at the beginning of the storm; second, that in areas where there was moisture in the soil not protected by a layer of snow, temperatures were so low that frost would inevitably form to considerable depths; and, third, that the alternate minor thawing and severe freezing, shown by the southern stations, tended to form layers of crust having a high water content. All these conditions were conducive to high rates of run-off when followed by the unusually high temperatures that prevailed from March 10 to 31, accompanied by heavy rains. The temperature conditions during the flood period from March 9 to 22, 1936, are shown on Fig. 9.

Rainfall

During the period March 9 to 22, 1936, four distinct storm centers passed over the northeastern part of the United States. The first disturbance, that of March 9 and 10, was accompanied by snow in northern New England. On March 10 a gulf disturbance was centered off the Georgia coast and moved northeastward with increasing intensity. By March 12 this disturbance had crossed Virginia, Maryland, Pennsylvania and New York. On the 13th the storm center had merged over western Quebec into a disturbance that had passed over the Great Lakes region on the preceding day. These disturbances were accompanied by heavy precipitation over the entire northeastern part of the United States. In this report the precipitation accompanying the general disturbances of March 8-10 and of March 11-12 has been treated as one general storm. Over the area as a whole, the greater part of the precipitation is recorded as having occurred on March 11 and 12. The center of maximum rainfall was in the White Mountain area in New Hampshire with secondary centers in southern

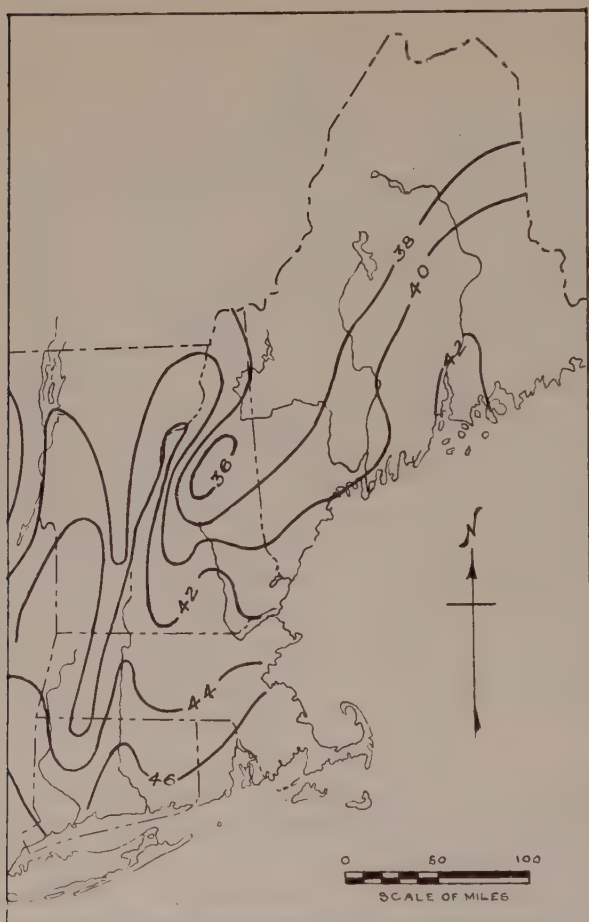


FIG. 9.—MAP OF NEW ENGLAND SHOWING ISOTHERMAL LINES OF MEAN TEMPERATURE, IN DEGREES FAHRENHEIT, MARCH 9-22, 1936.*

Vermont, in the Berkshire Hills in western Massachusetts and Connecticut. This precipitation during this storm in New England is shown on Fig. 10.

Precipitation over the Northeastern states was generally light on March 14 and 15 and accompanied a minor disturbance that passed over the Great Lakes and into Canada. On the 15th and 16th there was an area of outstanding low barometric pressure over the Gulf states. By the morning of the 18th this disturbance was over Vir-

*Taken from U. S. Geol. Survey Water Supply paper 798.

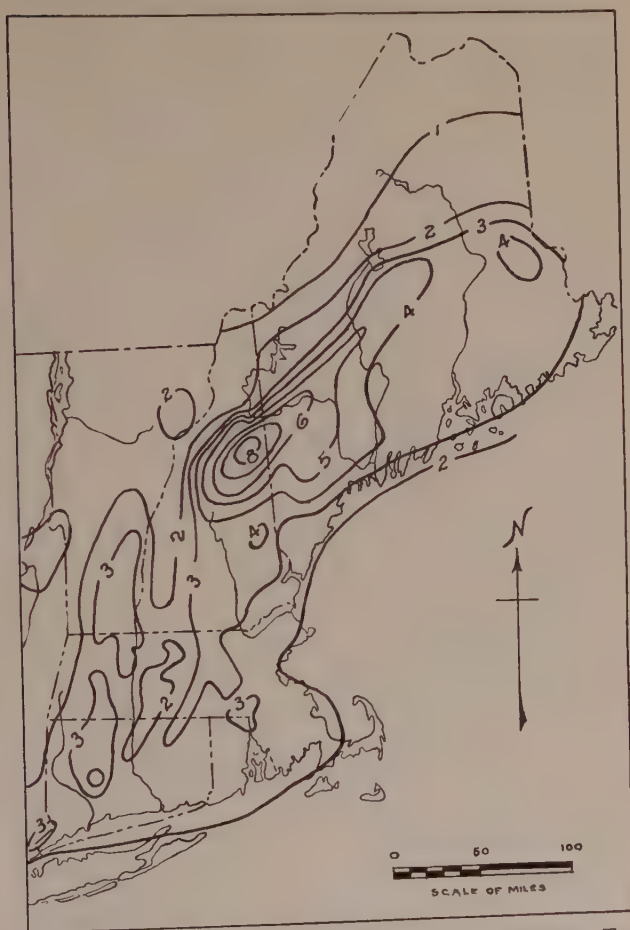


FIG. 10.—ISOHYETAL MAP OF NEW ENGLAND SHOWING THE TOTAL PRECIPITATION, IN INCHES, MARCH 9-13, 1936.*

ginia, and it passed over New Jersey and Connecticut on the 19th and over Quebec on the 20th. This disturbance was accompanied by general heavy precipitation over all of the areas affected by the floods. The major part of the rainfall was recorded on March 17 and 18. Although this heavy rainfall centered in the White Mountain area, it reached very considerable magnitude over most of central New England. On the 20th, 21st and 22nd another disturbance crossed the area, accompanied by minor rainfalls. The precipitation during the

*Taken from U. S. Geol. Survey Water Supply paper 798.

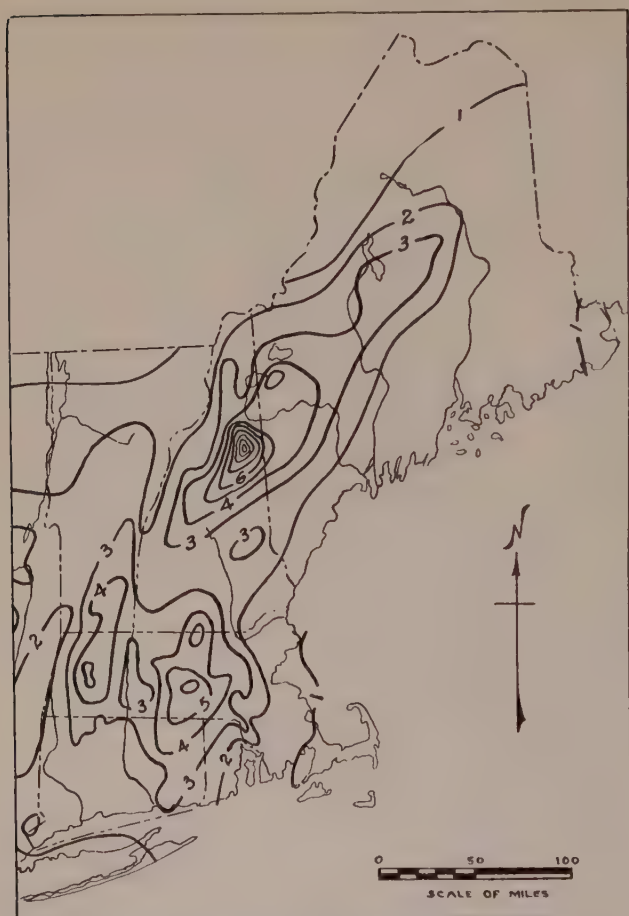


FIG. 11.—ISOHYETAL MAP OF NEW ENGLAND SHOWING THE TOTAL PRECIPITATION, IN INCHES, MARCH 16-19, 1936.*

second and major disturbance from March 16 to 19, 1936, is shown on Fig. 11.

Again on the 27th and 28th there was a minor storm which caused heavy precipitation in parts of New England, which, however, was not of sufficient magnitude to create an independent flood and was sufficiently delayed not to add to the major flood peaks. The rainfall associated with the major floods is that in the period March 9 to 22. The total rainfall for this period is shown on Fig. 12.

It is possible to appreciate the several storms which passed over

*Taken from U. S. Geol. Survey Water Supply paper 798.

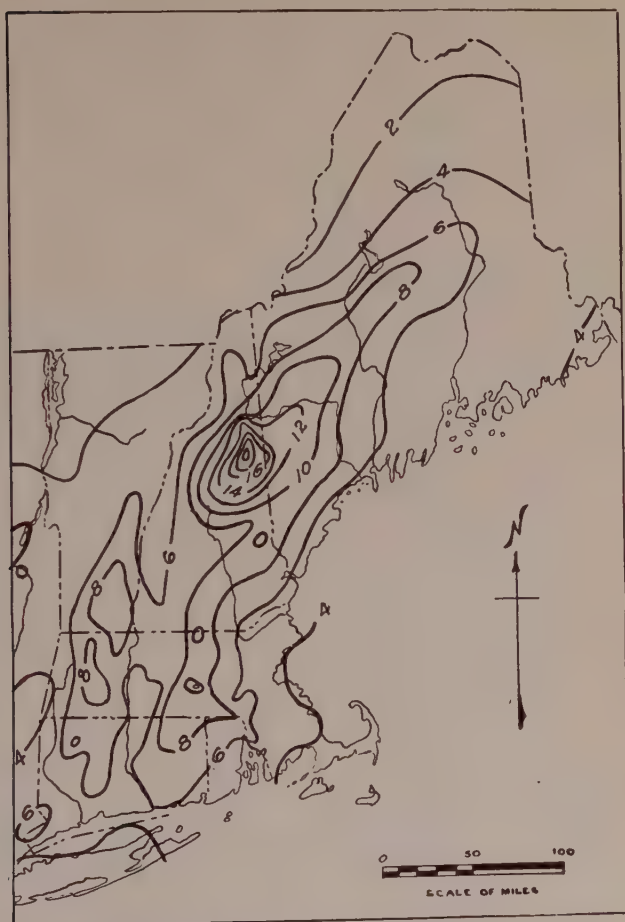


FIG. 12.—ISOHYETAL MAP OF NEW ENGLAND SHOWING TOTAL PRECIPITATION, IN INCHES.

the New England area during the period from March 9 to 22, 1936, by consideration of the chart shown as Fig. 13.

The areal extent of the individual storms in respect to depth of rainfall was approximately as follows:

Precipitation (inches)	Area covered (square miles)	
	First storm March 9-13	Second storm March 16-19
More than 8	170	150
" 6	1,300	6,700
" 4	7,900	43,500
" 2	76,000	163,000

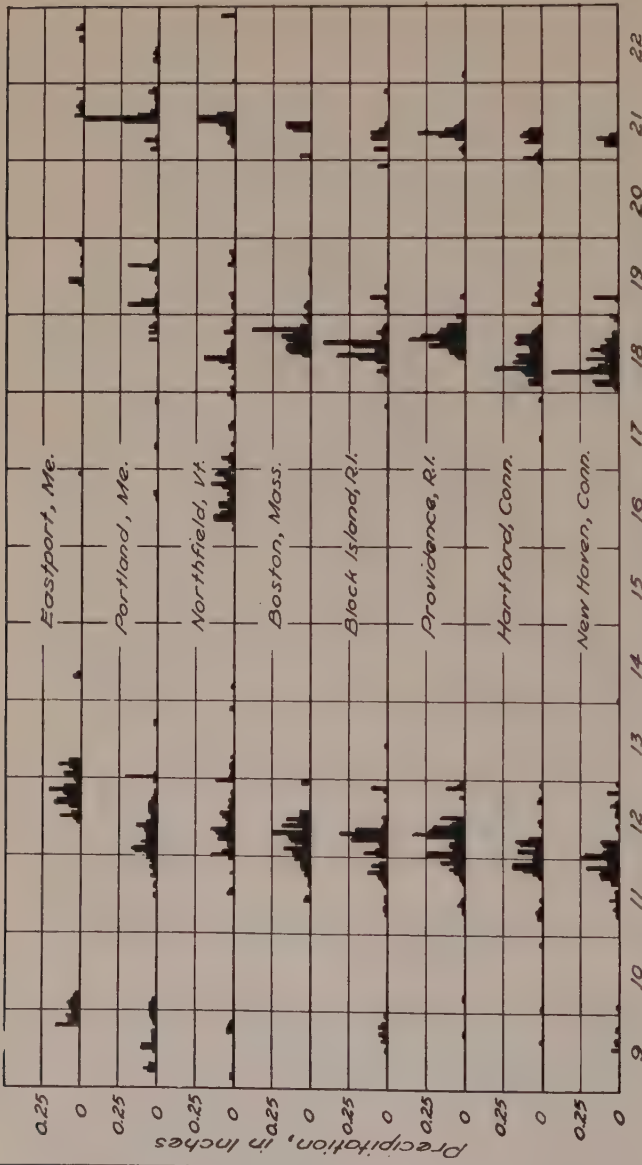


FIG. 13.—HOURLY PRECIPITATION AT VARIOUS UNITED STATES WEATHER BUREAU
PRECIPITATION STATIONS, MARCH 9-22, 1936.*

*Taken from U. S. Geol. Survey Water Supply paper 798.

The areal extent of the total storm period, March 9 to 22, in respect to depth of rainfall was approximately as follows:

Precipitation (inches)	Area covered (square miles)	Precipitation (inches)	Area covered (square miles)
More than 18	120	More than 10	4,000
" 16	300	" 8	19,000
" 14	800	" 6	66,000
" 12	1,500	" 4	168,000

In connection with the magnitude of the precipitation recorded for these storms, consideration should be given to the fact that the first heavy rain fell on a snow cover that had a water content of 5 to 10 inches or more in most of Massachusetts, Vermont, New Hampshire and Maine. The water content of the snow in northern Connecticut and eastern Maine was of lesser amount and little if any snow lay on the ground on the coastal areas of Connecticut, Rhode Island and southeastern Massachusetts. In respect to the amount and extent of precipitation, the first storm was notable but not extraordinary. It produced many serious ice jams and in certain areas larger floods than the second storm, but in general, it stands out only as a major contributing factor to the catastrophe that was to follow. The second storm was of sufficient magnitude and extent to rank with the great northern storms, although it was apparently exceeded in amount of precipitation by seven outstanding northern storms which have been analyzed by the engineering staff of the Miami Conservancy District.¹ These seven storms occurred on October 3-4, 1869; May 31 to June 1, 1889, May 19-21, 1894; July 12-14, 1897; November 3-4, 1927; March 24-25, 1913 and August 23-24, 1933. The storms of March 1936 occurred earlier in the year than any of the outstanding northern storms of record prior to that time. However, if the water content of the snow on the ground March 9, 1936, is taken into account, as well as the total rainfall for the period March 9-22, there appears to have been a greater amount of water over the area than had occurred at any previous time covered by the record.²

¹Storm Rainfall of Eastern United States, Miami Conservancy District Technical Department, Part V, Revised, 1936.

²A detailed description of the rainfall snow cover conditions on the individual watersheds in the New England area during the floods of March 1936 are given on pages 26 to 62 of U. S. Geological Survey Water-Supply Paper 798.

U. S. Geological Survey, Water-Supply Paper 800, "Floods of March 1936, The Potomac, James and Upper Ohio Rivers", includes a section entitled "Weather associated with the floods of March 1936" by Stephen Lichblau of the U. S. Weather Bureau which describes and analyzes the meteorologic phenomena incident to the floods including twelve explanatory charts and a bibliography of pertinent literature.

FLOOD OF SEPTEMBER 1938

During the brief interval of six hours on September 21, 1938, a West Indian hurricane passed over Long Island, N. Y., and New England. The hurricane as it struck New England, was the climax of a four-day period of rainfall which, in itself, was of outstanding amount and character, and which produced river stages that inundated and damaged nearly everything on the river flood plains. When measured by the appalling loss of life and property caused by the combined forces of the hurricane winds and the associated ocean storm waves and river floods, these events constituted the greatest catastrophe in New England since its settlement by the white man.

A tropical hurricane moving northward off the Atlantic Coast veered inland from the ocean on the afternoon of September 21 crossing Long Island, the coast of Connecticut and Rhode Island. The hurricane continued northward with almost unabated force through Connecticut and Massachusetts, and then gradually diminishing, crossed the Green Mountains in central Vermont and passed into Canada near Lake Champlain. New England had been experiencing heavy rainfall on Sept. 18, 19 and 20, when the rain just preceding the hurricane brought the total rainfall during a four-day period to a maximum of about seventeen inches in certain limited areas and an average of more than 11.5 inches over an area of 10,000 square miles.

Conditions Preceding the Hurricane

Although the time of occurrence of the major floods on the New England streams during September 1938, was coincident with the tropical hurricane that swept northward across New England on September 21, it appears that the magnitude of the floods may have been largely determined by meteorological conditions not intimately associated with the hurricane. It was not until September 16 that it had been definitely charted as a fully developed hurricane some 1,200 miles east of the south Atlantic coast, travelling in the usual course at the moderate speed of about twenty miles an hour. Prior to that time a continental disturbance centered over northern Maine on the afternoon of September 12 and was the cause of appreciable rainfall in the New England area. At the same time, a low-pressure area centered over Nebraska, moved along the regular paths eastward across the Ohio and St. Lawrence Valleys and by the afternoon of September 15 was over eastern Quebec. These disturbances brought 1-4 inches of rain to New England and eastern New York, Fig. 14, during

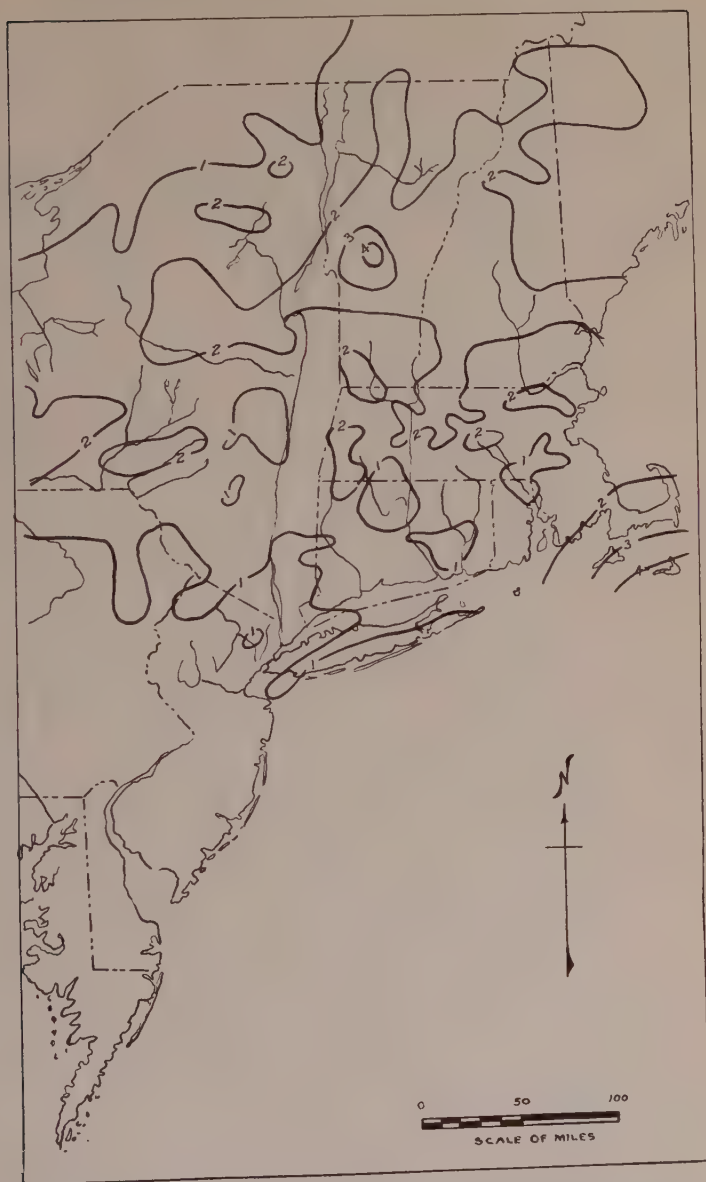


FIG. 14.—ISOHYETAL MAP OF THE NORTH ATLANTIC STATES SHOWING THE TOTAL PRECIPITATION, IN INCHES, DURING SEPTEMBER, 12-16, 1938.*

*Taken from U. S. Geol. Survey Water Supply paper 847.

the period from September 12 to 16, which in this report has been designated as the time of the first storm. The greatest recorded precipitation on any calendar day was between 1.5 and 2 inches. There was no appreciable flood run-off from the rainfall of the first storm, but a considerable part of the absorptive capacity of the ground had been utilized at the beginning of the second or major storm period, with the result that the magnitude and intensity of the flood run-off were correspondingly increased during the subsequent major storm.

The Major Storm and Hurricane

The major storm period began with light showers during the afternoon of September 17, after which, on September 18, there ensued a steady accumulation of precipitation generally increasing in intensity. The period closed abruptly with the passing of the hurricane during the afternoon and evening of September 21 (Fig. 15). The precipitation on September 17, 18 and 19 seems to have been indirectly associated with a rather severe continental disturbance that was situated over Lake Michigan and Lake Superior, and with the inflow of polar air from the high-pressure area that centered over Newfoundland. The weather maps for the mornings of September 18 and 19 show a well-defined front situated slightly to the east but parallel to the belt of maximum rainfall. The weather map for the morning of September 20 showed material alterations; the continental low-pressure area had diminished in depth and had moved to the northeast over Quebec. It was succeeded by a high-pressure area. An associated trough of low pressure had developed to the east of the coast extending from North Carolina into central New England. This trough was then situated between one high-pressure area over the eastern Great Plains and a second over Newfoundland and the North Atlantic Ocean. Into the trough so formed moist tropical air moved northward and aloft, causing copious rainfall over New England. Meanwhile the hurricane disturbance was progressing rapidly northward along the Atlantic coast between the nearly stationary high-pressure areas. On the morning of September 21 the low-pressure areas had united, and a deep trough of low barometric pressure remained over the coastal area from Cape Hatteras northward and over New England and eastern New York, along the center of which the hurricane was rapidly advancing northward. This sequence of meteorological conditions produced torrential rains that continued through

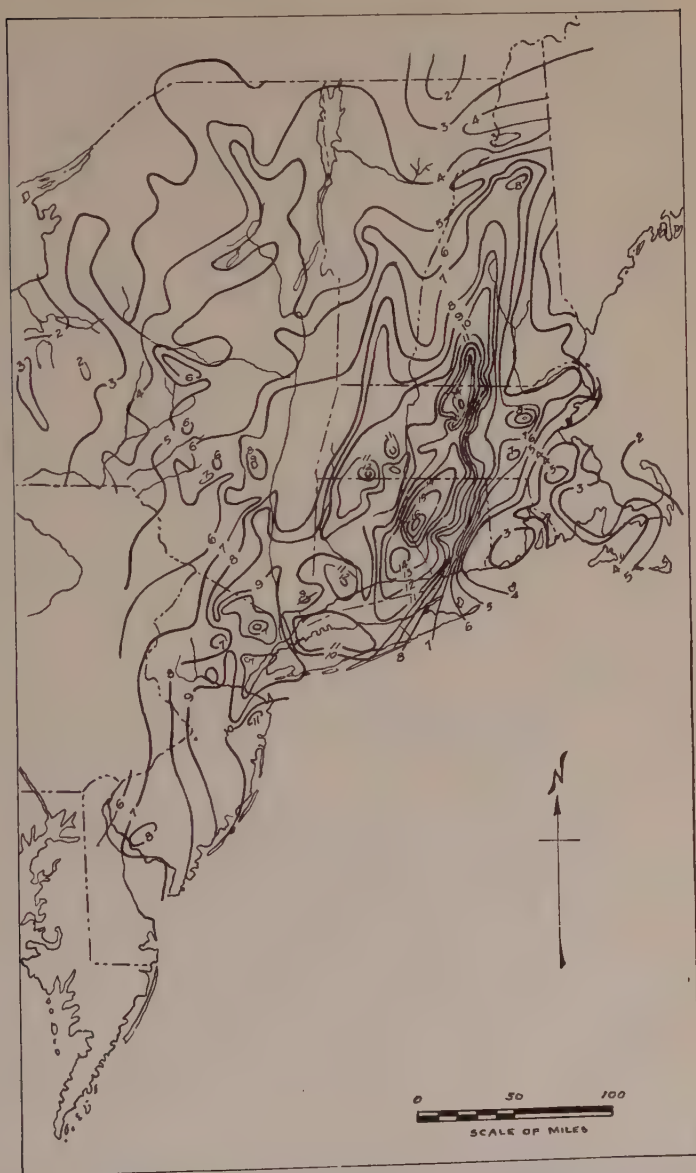


FIG. 15.—ISOHYETAL MAP OF THE NORTH ATLANTIC STATES SHOWING THE TOTAL PRECIPITATION, IN INCHES, DURING SEPTEMBER 17-21, 1938.*

*Taken from U. S. Geol. Survey Water Supply paper 847.

the afternoon of the 21st, generally culminating in high intensity rates and abruptly terminating with the passing of the central low-pressure area or hurricane. It is probable that the passage of the hurricane into and up this trough may have caused the end of the rain sooner than would have been the case without it, and thus reduced its amount.

The major storm period essentially embraces the rain that fell between the afternoon of September 17 and the evening of September 21. The rain during the 24 hours ending 6 p.m., September 18, was relatively light and produced but little direct run-off. The precipitation during each of the following three days was appreciable and was localized over nearly the same area and along nearly the same axis. An appreciable portion of the precipitation during the 24 hours ending at 6 p.m. September 21, was associated with the passing of the hurricane, and in general, exceeded the amounts recorded during the preceding 24-hour period; three inches is probably a fair estimate of the rain due solely to the hurricane.* In a very considerable part of Connecticut and central Massachusetts the total storm precipitation of September 17-21 exceeded 16 inches, and maxima of more than 17 inches were recorded in central Massachusetts and Connecticut. At Barre, Mass., 11.83 inches was recorded during the 24-hour period ending at 8 a.m. on the morning of September 21, a 24-hour maximum for the storm at any point where observations are available.

Antecedent Soil Conditions

To an important extent the foundation of a flood event may be laid during the period that precedes it. This is especially apparent in winter or spring, when the depth of snow accumulated through the preceding months, or the presence of frost in the ground, become of transcending importance as factors in the production of floods. During other seasons the preceding period affects chiefly the capacity of the soil and vegetation for retaining water, and includes as a principal factor the degree to which such capacity has been utilized by the antecedent rains. The factors that determine climate may, in their seemingly erratic variations from normal, result in corresponding variations in the retentive capacity of the soil. During the period preceding the flood of September 1938 the soil moisture tended to be stationary throughout the summer season, the normal tendency toward

*J. H. Kimball.

depletion being absent. The significance of this marked departure from normal is readily apparent. The monthly total precipitation and departure from normal in inches from April to September 16, 1938, inclusive is shown in Table 3.

TABLE 3.—MONTHLY TOTAL PRECIPITATION AND DEPARTURE FROM NORMAL, IN INCHES, APRIL TO SEPTEMBER 1938.

State	April		May		June	
	Total	Departure	Total	Departure	Total	Departure
New Hampshire	2.61	—0.42	3.10	—0.02	4.00	+0.45
Vermont	2.73	— .11	2.94	— .21	3.32	— .30
Massachusetts	3.04	— .52	3.92	+ .62	7.39	+3.89
Rhode Island	3.12	— .73	4.63	+1.21	7.18	+4.10
Connecticut	3.17	— .52	4.05	+ .41	6.92	+3.44

State	July		August		Sept. 1-16	
	Total	Departure	Total	Departure	Total	Departure
New Hampshire	7.24	+3.56	3.64	+0.05	2.80	+0.94
Vermont	6.84	+3.07	4.15	+ .55	2.86	+1.02
Massachusetts	8.97	+5.45	3.21	— .54	2.44	+ .53
Rhode Island	4.40	+1.33	3.38	— .31	2.05	+ .23
Connecticut	9.57	+5.61	4.20	+ .03	1.90	— .17

The amount of antecedent precipitation and temperature are of direct interest insofar as they affect the soil moisture, which may be

TABLE 4.—MONTHLY MEAN TEMPERATURE AND DEPARTURE FROM NORMAL, IN DEGREES FAHRENHEIT, APRIL-SEPTEMBER 1938.

State	April		May		June	
	Mean	Departure	Mean	Departure	Mean	Departure
New Hampshire	44.7	+2.7	52.5	—1.5	65.0	+2.0
Vermont	44.8	+3.2	52.8	—1.1	64.9	+1.9
Massachusetts	48.3	+3.1	55.0	—1.4	66.1	+1.0
Rhode Island	47.5	+2.0	54.6	—1.2	64.3	— .3
Connecticut	49.9	+3.3	55.8	+1.7	66.6	+ .5

State	July		August		Sept. 1-16	
	Mean	Departure	Mean	Departure	Mean	Departure
New Hampshire	68.5	+0.5	68.4	+3.0	55.0	—2.7
Vermont	68.3	+ .6	68.5	+3.3	56.0	—1.5
Massachusetts	71.0	+ .7	72.1	+3.7	62.6	+ .2
Rhode Island	71.0	+ .9	72.4	+3.3	60.4	+3.5
Connecticut	71.7	+1.0	72.4	+3.4	62.1	— .1

taken as a measure of the rain-absorbing capacity of the ground. The monthly mean temperature and departure from normal in degrees Fahrenheit for April to September 16, 1938, are shown in Table 4.

Precipitation

The hourly precipitation in inches preceding the floods of September 1938 for five New England stations are shown on Fig. 16. During the period from September 12 to 16 measurable precipitation fell everywhere over the New England states and reached a maximum of more than 4 inches in west-central Vermont and at Nantucket, Mass. Over the greater part of the area the rainfall was between 1 and 2 inches, somewhat irregularly distributed, and most of the rain fell during 24-hour periods ending on the evenings of September 12 and 15, respectively, although there were other scattered light rains. The total precipitation during the period September 17-21, as shown in Fig. 15, with a ridge of maximum precipitation occupy a well-defined position across New England from Long Island Sound to New Hampshire. The recorded maximum precipitation along this ridge

TABLE 5.—AREA-DEPTH DATA FOR RAINFALL OF SEPT. 17-21, 1938.

Isohyetal (inches)	Area (square miles)	Rainfall (mean depth, in inches)
Noon Sept. 17 to 12 p.m. Sept. 21		
16	100	16.8
14	835	15.0
12	2,670	13.6
10	9,020	11.7
8	20,300	10.2
6	36,000	8.85
4	58,600	7.35
24-hour period ending 6 p.m. Sept. 19		
4	135	4.50
3	2,010	3.55
2	12,580	2.65
24-hour period ending 6 p.m. Sept. 20		
4	990	4.75
3	5,450	3.75
2	27,200	2.75
24-hour period ending 6 p.m. Sept. 21		
6	1,020	6.55
4	16,000	5.02
2	52,400	3.55

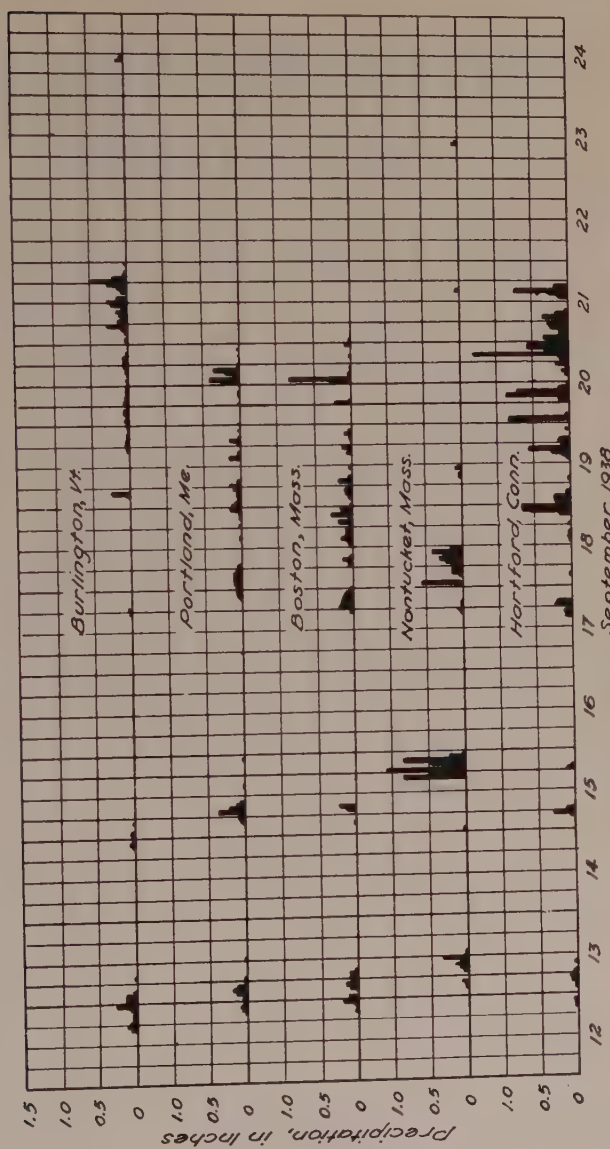


FIG. 16.—HOURLY PRECIPITATION AT VARIOUS PRECIPITATION STATIONS.*

*Taken from U. S. Geol. Survey Water Supply paper 867.

exceeded 17 inches at one station in Connecticut and one in Massachusetts. The extent of various rainfall accumulations are shown in Table 5.

That the storm remained localized in position during the 3 days of heaviest rainfall, September 19 to 21, is illustrated by Table 6,

TABLE 6.—DEPTH OF AVERAGE RAINFALL, IN INCHES, FOR INDICATED AREA AND PERIOD

Area (square miles) 1	24-hour period ending Sept. 19 2	24-hour period ending Sept. 20 3	24-hour period ending 6 p.m. Sept. 21 4	Sum of Column 2 to Column 4 5	Storm of Sept. 17-21 6
1	4.9	6.3	8.5	19.7	18.0
500	4.05	5.15	6.8	16.0	15.5
1,000	3.8	4.8	6.55	15.15	14.8
2,000	3.55	4.4	6.2	14.15	14.0
4,000	3.2	3.95	5.9	13.05	13.0
6,000	3.0	3.7	5.75	12.45	12.3
10,000	2.75	3.4	5.45	11.6	11.5

The extent to which the figures in column 5 agree with those in column 6 indicates the degree of geographical coincidence of areas of maximum rainfall during the selected storm periods.

which emphasizes the fact that the areas of heaviest rainfall during each of the 3 days were nearly coincident. Comparison of these results with those of previous storms in the region, as reported by the Miami Conservancy District, as shown on Table 7, indicate that in

TABLE 7.—DEPTH OF AVERAGE RAINFALL IN RELATION TO AREAL EXTENT FOR NOTABLE STORMS

Date of Storm	Center of storm	Average rainfall, in inches, over indicated area, in square inches						Duration (days)
		1	500	1,000	2,000	4,000	6,000	
1869 Oct. 3-4 ^a	Conn.	12.4	10.4	9.7	8.9	8.1	7.8	2
1897 July 12-14 ^a	do.	10.3	9.5	9.1	8.5	7.5	6.9	2
1927 Nov. 3-4 ^a	Vt.	9.4	9.1	8.9	8.6	8.1	7.7	2
1932 Sept. 16-17 ^b	R. I.	12.2	11.2	10.4	9.4	8.3	7.8	1
1936 Mar. 9-13	New England	9.2	7.9	7.3	6.6	5.9	5.45	4
1936 Mar. 16-19	do.	9.0	8.0	7.7	7.4	7.0	6.8	3
1938 Sept. 17-21	do.	18.0	15.5	14.8	14.0	13.0	12.3	4

^aData given in Storm rainfall of eastern United States, part V, Tech. Repts. Miami Conservancy District, p. 178, Revised 1936.

^bBased on data of Geo. V. White, Great Storm of September 16 and 17, 1932: New England Water Works Assoc. Jour., vol. 47, No. 2, pp. 164-183, 1933.

respect to depth of rainfall and area covered the 4-day storm of September 17-21, 1938, has not been surpassed by any storm of like duration of which there is record.

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CHAPTER IV

1936 and 1938 Flood Runoff Data

The New England floods of 1927, 1936 and 1938 were record-breaking in many respects, but the single feature of greatest interest to the engineers for a given point along the river is the maximum flood discharge and the corresponding stage. Probably equal in importance for the purpose of extensive river studies is the hydrograph of run-off for the entire flood. The first requires a flood flow determination at the peak of the flood only, while to obtain the second it is necessary to have frequent determinations of discharge from the beginning to the end of the flood rise. Flood flow data in such detail can best be obtained by the regular operation of stream gaging stations, or from the collection of sufficient suitable records from dams having certain essential qualifications.

Maximum flood flows can be obtained at regularly operated stream gaging stations, at dams, or at miscellaneous points. At gaging stations where the stage-discharge relation is not defined by current-meter discharge measurements up to maximum stages, and at miscellaneous points where no current-meter measurements are available, maximum flows have been determined generally by one of three methods: (1) Computation of flow over dams, (2) Computation of flow from slope-area surveys, (3) Computation of flow through contracted openings. The U. S. Geological Survey has published examples and general information in regard to the use of these methods in Water Supply Papers 773-E, 796-G, 798, 800 and 816.

A compilation of the flood flow determinations made by the U. S. Geological Survey of the 1927 flood has been published in U. S. Geological Survey Water Supply Paper 636-C and in the Journal of the Boston Society of Civil Engineers for September 1930. Similar compilations of flood flow including gage height and discharge hydrograph data were published in U. S. Geological Survey Water Supply Paper 798 for the flood of 1936 and in No. 867 for the flood of 1938. To be published soon is a report on the floods of January and July, 1938.

In Table 8 is listed a small part of the maximum flood flow and precipitation data taken from the above-mentioned publications. This table makes it possible to compare the magnitude of the three floods

TABLE 8.—FLOOD FLOW, RUN-OFF AND PRECIPITATION DATA NEW ENGLAND RIVERS

Stream and Place of Determination	Drainage Area		Record Began	Maximum Discharge known before 1936 Date	Discharge before 1936 Sec.-ft.	Maximum Discharge		Flood of March 1936		Snow Water plus pre- cipitation	Flood Run-off	Per cent Collected	Flood of September 1938				
	Total	Uncontrolled				Sec.-ft.	per sq. mi.	Water in Precipitation Mar. 9-22	Sec.-ft.				per sq. mi.	Maximum Sec.-ft.	Discharge per sq. mi.	Precipitation Sept. 17-21	Flood Run-off
Penobscot, West Enfield, Me.	6,600	4,690	1901-	1923	153,000	125,000	19.9	8.6	5.3	13.9	8.75 ^a	63					
Kennebec, Waterville, Me.	4,270	3,030	1892-	1901	157,000	154,000	36.1	9.2	6.6	15.8	9.20 ^a	58					
Androscoggin, Rumford, Me.	2,090	1,248	1892-	1895	55,200	74,000	35.4	10.4	8.65	19.05	11.41 ^a	60					
Saco, Conway, N. H.	386	386	1903-10; 1929-	1907	24,000	40,600	105	9.1	17.5	26.6	15.96	60	20,800	53.9			
Pemigewasset, Plymouth, N. H.	622	622	1903-	1927	60,000	65,400	105	7.2	10.2	17.9	15.2	85	50,900	81.8	7.65	5.4 71	
Merrimack, Franklin Jct., N. H.	1,507	935	1903-	1927	63,000	83,000	55.1	5.9	9.4	15.3	12.65 ^a	83	59,200	39.3	7.35	4.25 58	
Merrimack, Lawrence, Mass.	4,672	3,930	1879-	1852	108,000	174,000	37.2	4.0	8.2	12.2	11.53 ^b	95	121,100	26.1	7.95	3.7 ^b 47	
Blackstone, Woonsocket, R. I.	416	—	1929-	1927	14,700	15,000	36.0	2.1	8.4	10.5	10.35	99	6,130 ^c	14.7			
Quinebaug, Jewett City, Conn.	711	711	1918-	1935	13,100	29,200	41.1	2.6	8.1	10.7	9.42	88	22,800	32.1	8.9	4.3 48	
Shetucket, Willimantic (S. Windham), Conn.	401	401	1919-21; 1928-	1934	19,800	23,700	59.6	2.4	7.85	10.25	9.88	96	52,200	1.30	14.0	7.7 55	
Connecticut, South Newbury, Vt.	2,825	2,750	1918-	1927	65,900	77,800	27.5	7.8	5.85	13.65	9.67 ^a	71	43,700	15.5	4.2	2.2 52	
Connecticut, White River Jct., Vt.	4,068	3,990	1911-	1927	136,000	120,000	29.5	7.6	5.65	13.25	10.72 ^a	81	82,400	20.3	4.6	2.35 51	
Connecticut, Montague City, Mass.	7,840	—	1904-	1927	179,000	236,000	30.1	6.7	6.3	13.0	10.89 ^a	84	195,000	24.9	6.4	3.7 58	
Connecticut, Holyoke, Mass.	8,284	—	1860-	1927	183,000	244,000	29.5	6.5	6.35	12.85	11.42 ^a	89	189,000	22.8	6.65	3.7 56	
Connecticut, Springfield, Mass.	9,587	—	1801-	1927	188,000	281,000	29.3						235,000	24.5	7.3	4.05 56	
Connecticut, Thompsonville, Conn.	9,637	—	1928-	1927	190,000	282,000	29.3	6.3	6.45	12.75	11.18 ^a	88	236,000	24.5	7.3	4.05 56	
Connecticut, Hartford, Conn.	10,480	—	1639-	1854	—	313,000	29.9						251,000	24.0	7.55	4.05 54	
White, West Hartford, Vt.	690	690	1915-	1927	120,000	45,400	65.8	7.4	5.25	12.65	10.10	80	47,600	69.0	5.5	3.1 56	
West, Newfane, Vt.	308	308	1919-	1927	45,000	39,000	127	7.3	7.65	14.95	11.70	78	52,300	170	8.4	5.05 60	
Ashuelot, Hinsdale, N. H.	420	420	1907-	1920	18,000	16,600	39.5	4.7	6.8	11.5	10.89	95	16,200	38.6	8.5	5.35 63	
Millers, Erving, Mass.	370	—	1914-	1933	6,000	19,700	53.2	5.2	6.95	12.15	11.62	96	29,000	78.4	12.35	7.9 64	
Deerfield, Charlemont, Mass.	362	178	1913-	1915	38,200	32,200 ^d	181 ^d	7.4	7.95	15.35	13.64	89	56,300 ^d	316 ^d	8.8	7.1 82	
Ware, Gibbs Crossing, Mass.	199	199	1912-	1933	2,960	11,200	56.3	3.8	7.3	11.1	9.77	88	22,700	114	13.0	8.1 62	
Chicopee, Bircham Bend, Mass.	703	—	1928-	1933	6,790	20,400	29.0	4.0	7.2	11.2	9.03	81	45,200	64.3	12.15	7.85 65	
Swift, West Ware, Mass.	186	—	1910-	1923	2,390	7,590	40.8	4.5	6.85	11.35	9.13	80	5,540 ^e	29.8 ^e	11.4	6.4 56	
Quaboag, West Brimfield, Mass.	151	151	1909-	1920	1,980	3,620	24.0	3.4	9.1	12.5	11.06	88	8,470	56.1	11.9	9.25 78	
Westfield, Knightville, Mass.	162	162	1909-	1927	16,000	25,700	159	5.6	8.0	13.6	11.47	84	37,900	234	9.75	5.8 60	
Westfield, Westfield, Mass.	497	497	1914-	1927	42,500	48,200	97.0	5.3	8.0	13.3	10.96 ^a	82	55,500	112	10.05	5.3 53	
Farmington, New Boston, Mass.	92	74.8	1913-	1927	6,610	9,080	98.7	6.0	7.3	13.3	11.65	88	18,500	201	11.0	7.9 72	
Hockanum, East Hartford, Conn.	74.5	74.5	1919-21; 1928-	1934	1,640	1,530	20.5	1.1	5.55	6.65	4.96 ^a	75	5,160 ^f	69.3	14.7	6.75 46	
Housatonic, Great Barrington, Mass.	280	280	1913-	1927	7,910	8,990	32.1	5.6	5.6	11.2	9.35	83	11,520	41.1	8.1	5.05 62	
Housatonic, Stevenson, Conn.	1,545	—	1928-	1934	23,700	69,500	45.0	4.0	5.45	9.45	8.42	89	59,500	38.5	9.2	5.25 57	
Naugatuck, Naugatuck, Conn.	246	246	1918-	1927	18,300	14,800	60.2	3.7	6.5	10.2	6.85	67	17,000	69.1	10.3	3.85 37	
No. Branch Hoosic, No. Adams, Mass.	39	39	1931-	1927	9,980	6,100	156	7.4	6.9	14.3	13.71	96	8,950	229	7.75	6.65 86	
Otter Creek at Middlebury, Vt.	628	—	1903-7; 10-20; 1928-	1927	13,600	11,000	17.5	6.5	4.7	11.2	8.46	76	6,630	10.6	5.7	2.95 52	
Winooski, Montpelier, Vt.	433	—	1909-	1927	57,000	20,000	46.2	7.4	4.95	12.35	10.02 ^a	81	14,000	32.3	4.0	1.4 35	

^a Corrected for storage.^b Measured below Concord River at Lowell.^c Highest known discharge, 15,100, July 24, 1938.^d From uncontrolled area.^e Affected by storage in Quabbin Reservoir.^f 2,140, Jan. 25, 1938.

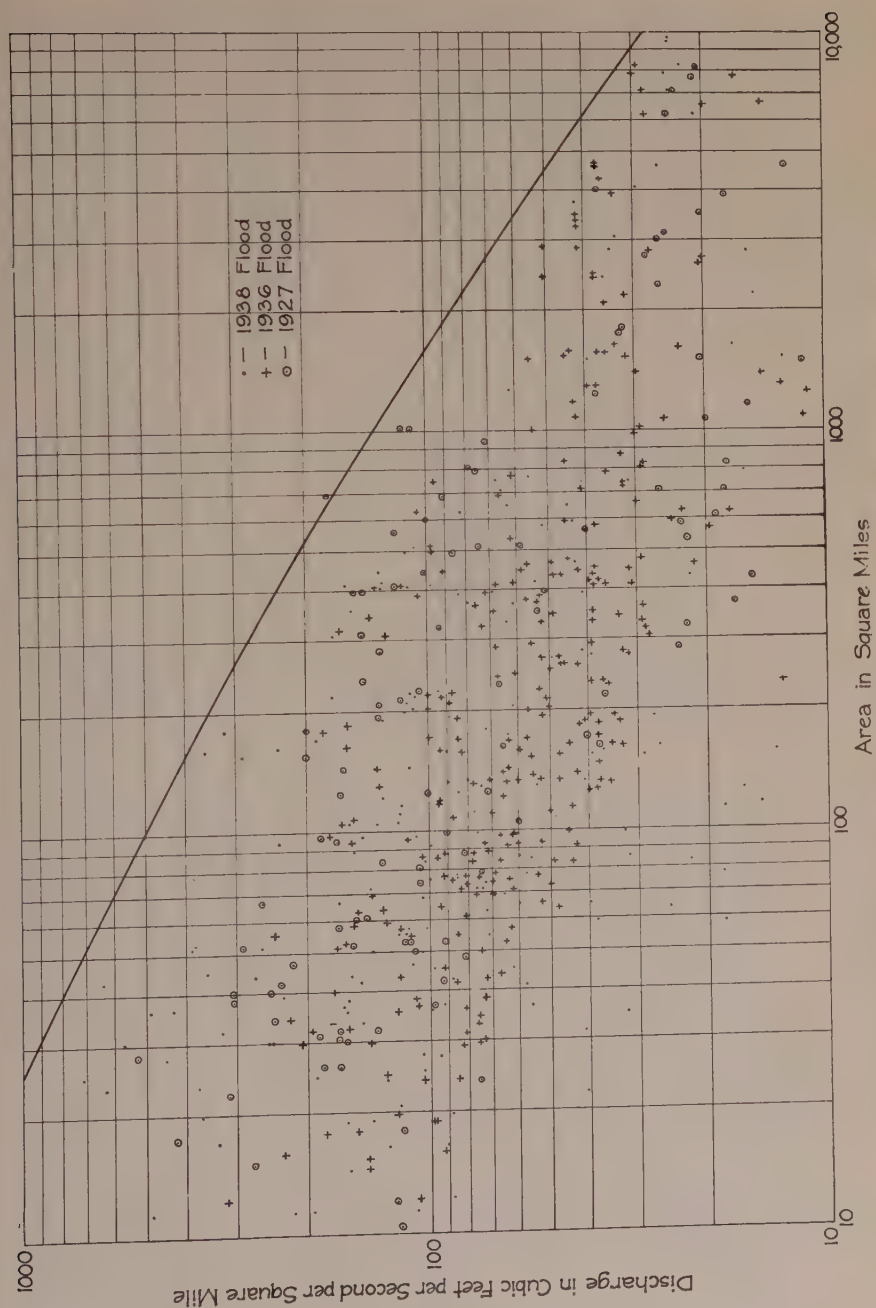


FIG. 17.—ENVELOPING CURVE OF PEAK DISCHARGES IN NEW ENGLAND RIVERS DURING THE 1927, 1936 AND 1938 FLOODS.

at a number of points in New England. It also indicates the area in which each flood was concentrated. The table shows the percentage of the total precipitation (including, for the 1936 flood, the water from snow) passing the stream gaging stations. The percentage collected during the March, 1936, flood in Maine is low because much of the snow remained on the ground after the flood. In the rest of New England, the percentage collected was very high. The percentage collected in the 1938 flood was much lower, averaging about 60 per cent.

The highest flood flow values in second-feet per square mile from these publications are plotted against the corresponding drainage areas on Fig. 17 which defines the enveloping curve determined by these floods. In general, the discharges are given as observed and many are affected by artificial storage or release of stored water resulting from failures of dams.

FLOOD PROFILES AND FLOODED AREAS

During the peak, or immediately thereafter, of the floods of 1936 and 1938, and to some extent in 1927, various state and federal governmental agencies, public service companies and many private individuals marked or located the elevation of the maximum flood crest reached by the rivers seriously affected by the floods. The major part of this work for the 1936 and 1938 floods in New England was done by the Corps of Engineers, U. S. Army, the Connecticut State Water Commission and Massachusetts Geodetic Survey with the Works Progress Administration. During the surveys following the floods, these flood elevations were in most cases referred to mean sea level datum of the United States Coast and Geodetic Survey. In the published tables is given the time of the peak at as many points on the river as could be accurately determined. From this information can be computed the time of transit of the flood peak. In Massachusetts, the areas flooded at the time of the 1936 flood were surveyed by the Massachusetts Geodetic Survey, Works Progress Administration. Maps showing these flooded areas were prepared and published in "High Water Data, Flood of March 1936 in Massachusetts".

The following list gives, for the rivers surveyed, the reference as to where the data may be obtained. The reference may be identified by letter shown below; the number following the letter gives the page number.

- a = 1938 flood, U. S. Geological Survey, Water Supply Paper 867.
 b = 1936 flood, U. S. Geological Survey, Water Supply Paper 798.
 c = 1927 flood, Journal, Boston Society of Civil Engineers, September, 1930.
 d = Mass. Geodetic Survey, Highwater Data, Flood of March 1936 in Massachusetts.
 e = Mass. Geodetic Survey, Highwater Data, Floods of March 1936 and September, 1938.

Penobscot River Basin

Penobscot, b, 377 Piscataquis, b, 377 Stillwater, b, 378

Kennebec River Basin

Kennebec, b, 378 Carrabasset, b, 380 Sandy, b, 381
 Sebacicook, b, 381 East Branch of Sebacicook, b, 382

Androscoggin River Basin

Androscoggin, b, 382 Swift, b, 385 Webb, b, 385
 Nezinscot, b, 386 Little Androscoggin, b, 386

Saco River Basin

Saco, b, 387 Ossipee, b, 390

Piscataqua River Basin

Salmon Falls, b, 390 Piscataqua, b, 391 Branch, b, 391

Merrimack River Basin

Pemigewasset, a, 477; Merrimack, a, 477; Blackwater, a, 482;
 b, 392 b, 393; c, 326; b, 399
 Newfound, a, 479; d, 106; e, 117 Whitman, b, 403
 b, 397 Contoocook, a, 479; Assabet, b, 406; d, 118
 Suncook, b, 399 b, 397 Shawsheen, d, 109
 Phillips Brook, d, 128 Souhegan, a, 482; S. Br. Nashua, b, 406
 Nashua, a, 484; b, 401 Concord, a, 484;
 b, 404; d, 123 North Nashua, a, 483; b, 407; d, 114
 Spicket, d, 106 b, 403; d, 128 Parker, d, 85
 Sudbury, a, 485;
 b, 408

Ipswich River Basin

Ipswich, b, 408; d, 84

Mystic River Basin

Aberjona, b, 408; Mystic, b, 409; d, 138
d, 138

Charles River Basin

Charles, b, 409; d, 44

Neponset River Basin

Neponset, b, 411; d, 143

Providence River Basin

Kettle Brook, b, 412 Blackstone, b, 412; d, Tatnuck, d, 36
Mumford, d, 36 36; e, 23
Quinsigamond, d, 36

Thames River Basin

Willimantic, a, 486; Shetucket, b, 413 Still, a, 487; b, 414
b, 413 Quinebaug, a, 487; b, Yantic, a, 488; b, 417
Natchaug, a, 487; 415; d, 153; e, 157
b, 414 French, b, 416;
d, 156; e, 163

Connecticut River Basin

Connecticut, a, 488;	Sandy Brook, a, 509	W. Br. of Westfield, a,
b, 417; c, 324;	Naugatuck, b, 436	508; b, 434
d, 54; e, 31	Lamoille, c, 321	Still, a, 509
Moose, b, 423	Ammonoosuc, b, 423	Housatonic, b, 434;
Waits, b, 424	Tabor Brook, b, 424	e, 141
Ottauquechee, b, 425	Sugar River, b, 426	E. Br. Naugatuck, b,
West, a, 491; b, 427	Orcutt Brook, a, 493	437
Otter Brook, a, 495	Minnewawa Brook, a,	Passumpsic, b, 422
S. Br. of Ashuelot,	495	Wells, b, 424
a, 496	Millers River, a, 496;	White, b, 424
Priest Brook, a, 499	b, 428; d, 80; e, 95	Saxtons, b, 426
Deerfield, a, 400;	Otter, a, 499; d, 80;	Ashuelot, a, 493;
b, 430; d, 70; e, 79	e, 109	b, 427
East Branch of North,	North River, a, 503;	Beaver Brook, a, 496
a, 503	d, 70	Tully, a, 500; d, 80;
Ware, a, 503; b, 430;	Chicopee, a, 503;	e, 99
d, 63; e, 69	b, 431; d, 60; e, 45	Green, a, 503

Swift, a, 504; b, 432	Quaboag, a, 504;	Sevenmile, a, 505
Fivemile, a, 505	b, 432; d, 63; e, 55	Mad, a, 509
Middle Br. of West-	Westfield, a, 505;	Hoosac, e, 131
field, a, 507	b, 433; d, 58; e, 39	Winooski, c, 320
Farmington, a, 508;		
b, 434		

EFFECT OF EXISTING STORAGE RESERVOIRS

There are many existing reservoirs in New England constructed and operated exclusively to conserve water, which have a decided incidental effect in reducing flood peaks. The water stored in these reservoirs is used primarily to generate power at downstream hydroelectric plants or to create a water supply for a nearby municipality, and in some cases, such as Cobble Mountain Reservoir, Table 9, No. 13a, for both purposes. These reservoirs have a large storage capacity per square mile of drainage area and, if empty, will store all the water flowing into them in an ordinary flood. The effect of these reservoirs in periods of flood varies from a complete elimination of the flood wave in the river directly below the reservoir dam if the reservoir is empty, to a delay in the time the flood peak passes the dam, if the reservoir is full. In the first case, a substantial reduction in flood peak is made at points downstream; in the second case, peak reductions are obtained if the delayed overflow does not coincide more closely with that from other portions of the drainage area.

Water supply reservoirs are drawn at comparatively uniform rates and if this draft approaches the yield of the drainage area the water surface elevation in the reservoir may be below the spillway level for long periods at a time. The elevation of the water surface will rise rapidly during periods of high runoff and gradually lower during dry periods with only infrequent wasting of water over the spillway.

Power storage reservoirs are operated by an entirely different method. The drafts vary considerably, ranging from no discharge to flows far in excess of the natural flows. The full capacity of the reservoir is generally used at least once a year. The operation is such as to assist power development downstream to utilize a maximum amount of the runoff in the river. During periods of high water the stream flow from the drainage area below the storage reservoir is often sufficient to operate the power developments. At such times it is

TABLE 9.—BASIC DATA ON EXISTING STORAGE RESERVOIRS STUDIED

Reser- voir No.	River and Reservoir	Use of Reservoir*	Drainage Area Sq. Miles	Area Water Surface at Spillway Acres	Total	Storage Capacity Total Per Sq. Mi.	Million cu. ft. Usable	Per Sq. Mi.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
<i>Androscoggin River, Me.</i>								
1a	Rangely Lake	P.S.	90		1,339	14.9		
1b	Mooselooknuguntic L.	P.S.	405		8,370	20.7		
1c	Richardson Lakes	P.S.	509		5,691	11.2		
1d	Umbagog Lake	P.S.	1,095		3,080	2.81		
1e	Kennebago Lake	P.S.	112		1,118	10.0		
1f	Aziscohos Res.	P.S.	233	6,730	9,593	41.2		
<i>Presumpscott River, Me.</i>								
2	Sebago Lake	P.S.	436		9,700	22.2		
<i>Winnepesaukee R., N. H.</i>								
3	Lake Winnepesaukee	P.S.	363	44,586	18,240	50.3	7,700	21.2
<i>Asnebumskit Brook, Mass.</i>								
4a	Pine Hill Res.	W.S.	9.43		396			
4b	Kendall Res.	W.S.			115			
<i>Br. Mystic R., Mass.</i>								
5	Winchester Res.	W.S.	1.25		20	16.0		
<i>Stony Brook, Mass.</i>								
6a	Hobbs Brook Res.	W.S.			434			
6b	Stony Brook Res.	W.S.	23.6		54	2.3		
<i>Ramford River, Mass.</i>								
7a	Norton Res.	W.S.	17.4		20	1.1		
<i>Pawtuxet River, R. I.</i>								
8	Scituate Res.	W.S.	92.8		4,946	53.1		

TABLE 9.—(continued)

Reservoir No.	River and Reservoir	Use of Reservoir*	Drainage Area Sq. Miles	Area Water Surface at Spillway Acres	Storage Capacity		Million cu. ft.	
					Total	Per Sq. Mi.	Total	Usable Per Sq. Mi.
<i>Connecticut River, N. H.</i>								
9a	1st Conn. Lake	P.S.	83.0	3,125			3,332	40.1
9b	2nd Conn. Lake	P.S.	45.4	1,272			506	11.1
<i>Mascoma River, N. H.</i>								
10a	Mascoma Lake	P.S.	153	1,476			450	2.9
10b	Crystal Lake	P.S.	9.9 net	395			140	14.1 net
10c	Goose Pond	P.S.	15.7	668			478	30.5
10d	Grafton Pond	P.S.	3.3	321			140	42.4
<i>East Br. Deerfield R., Vt.</i>								
11	Somerset Res.	P.S.	30.0	1,623			2,500	83.3
<i>Deerfield River, Vt.</i>								
12	Harriman Res.	P.S.	154 net	2,184			5,056	32.8 net
<i>Westfield Little R., Mass.</i>								
13a	Cobble Mountain Res.	P.S.&W.S.	45.8		3,035)	73.8	3,034)	73.8
13b	Bordon Brook Res.	P.S.&W.S.			345)		345)	
<i>Br. Farmington R., Mass.</i>								
14	Otis Reservoir	P.S.	17.2	1,430	1,300	75.6	780	45.3
<i>Hockanum River, Conn.</i>								
15	Shenipsit Lake	P.S.&W.S.	16.5	625	4,700	285.	500	30.3
<i>Shepaug River, Conn.</i>								
16	Shepaug Res.	W.S.	38.0	96	96.1	2.5	76.8	2.0
<i>Rocky River, Conn.</i>								
17	Candlewood Lake	P.S.	40.4	5,608	—	—	6,210	154
<i>Br. Naugatuck R., Conn.</i>								
18	Wigwam Reservoir	W.S.	18.0	100	97.5	5.4	—	—

TABLE 9 (Continued)

Reser- voir No.	River and Reservoir	Use of Reservoir*	Drainage Area Sq. Miles	Area Water Surface at Spillway Acres	Total	Storage Capacity Per Sq. Mi.	Million cu. ft. Total	Usable Per Sq. Mi.
<i>Indian River, N. Y.</i>								
19	Indian Lake Res.	P.S.	131	5,000			4,700	35.8
<i>Sacandaga River, N. Y.</i>								
20	Sacandaga Res.	C.R.	1,044	26,700	37,720	36.1	33,120	
<i>W. Canada Creek, N. Y.</i>								
21	Hinckley Res.		375					
<i>Schoharie Creek, N. Y.</i>								
22	Schoharie Res.	W.S.	314		2,881	9.2	3,320	8.8
<i>Rockaway River, N. J.</i>								
23	Boonton Res.	W.S.	119				870	7.3
<i>Wanaque River, N. J.</i>								
24	Wanaque Res.	W.S.	90.4				3,476	38.5
<i>Lawrence Brook, N. J.</i>								
25	Farrington Dam Res.	W.S.	34.4				87.6	2.5
<i>Wallenpaupack R., Pa.</i>								
26	Wallenpaupack Lake	P.S.	228		9,350	41.0	6,950	30.6
<i>Mongaup River, N. J.</i>								
27a	Swinging Bridge Res.	P.S.	118		1,600	13.6	1,387	11.7
27b	Toronto	P.S.			1,200		1,108	
<i>Waterbury River, Vt.</i>								
28	Waterbury Res.	C.R.	109		2,807	25.7		

* Use of Reservoir

P.S. = Power Storage

W.S. = Water Supply

C.R. = Conservation Reservoir

economically advantageous to have some capacity available in the storage reservoir so that surplus water in the stream, not needed at the power development, can be stored upstream in the reservoir and not wasted over the power dams. Stored water produces income only after it has passed through the water wheels and generated power. For this reason, stored water is released in part or in whole as soon as it can be profitably used and capacity is thereby provided for the next period of high water. Because of this method of operation, there is usually available in a power storage reservoir a certain amount of capacity for flood storage at such times as floods may normally be expected. The operation of power reservoirs is based on studies of past experience of stream flow at the site of the reservoir which makes possible a fairly accurate estimate of the probable periods of high water.

Existing storage reservoirs had a substantial effect on the flood flows of the river on which they were located during the floods of March, 1936, and September, 1938. Data showing the behavior of forty such reservoirs during one or both of these floods are available and the results of studies of these reservoirs are contained in Tables 9, 10 and 11. Basic information on the drainage area, water surface area, and storage capacity for each of these forty reservoirs is given in Table 9. The effect of these reservoirs on the March, 1936, and September, 1938, average daily flood peaks is given in Tables 10 and 11 respectively. The amount of storage available at the beginning of the flood is given in Columns 4 and 5, and the actual amount of storage used may be found in Columns 6 and 7. The estimated per cent reduction in flood peak at the reservoir outlet produced by the reservoir is given in Column 14.

The March, 1936, flood occurred at a time of the year when floods are normally expected. For this reason all power reservoirs had available for use practically their total storage capacity and water supply reservoirs were well drawn down. A substantial reduction in flood peak could, therefore, be expected and such is indicated in Column 14 of Table 10. The flood of September 1938 occurred at a time when many of the reservoirs were drawn so as to provide sufficient capacity for a normal fall runoff. Because of the abnormal size of the flood, more reservoirs spilled water than in the 1936 flood.

There were many cases in both floods where 100% reduction in flow occurred, or a complete elimination of flow in the stream at the reservoir dam. In some cases 100% reduction could have been made had not water been released for beneficial use. There were several

TABLE 10.—EFFECT OF EXISTING STORAGE OF FLOOD FLOWS
FLOOD OF MARCH, 1936

At Outlet of Res. No. (1)	Ref.* (2)	Drainage Area, Sq. Mi. (3)	Storage Capacity—Million cu. ft. Available at Beginning of Flood Total Per sq. mi. (4)	(5)	Used During Flood—March 1936 Total Per sq. mi. (6)	(7)	Date (8)	Observed Peak Av. Daily Flow c.f.s. (9)	c.f.s./s.m. (10)	Date (11)	Estimated Peak Av. Daily Flow Without Storage c.f.s. (12)	c.f.s./s.m. (13)	Estimated Per cent Reduction of Peak Flows (14)
1d	119	1,095	23,404	21.4	19,194	17.5	3/21	12,400	11.3	3/19	52,280	48.0	76.3
1f	126	233	9,263	39.7	5,310	22.8				3/19	12,800	55.0	100.0
2	131	436	5,378	12.3	7,246	16.7	3/30	3,410	7.8	3/20	10,510	24.1	67.5
3	159	363	7,700	21.2	9,009	24.8	3/31	2,890	8.0	3/19	27,600	76.0	89.5
4	168	9.43			159	16.9	3/19	307	32.5	3/18	510	54.1	39.7
5	172	1.25			19	15.4	3/22	9	7.4	3/12	56	44.8	83.4
6	175	23.6	199	8.4	128	5.4	3/12	443	18.8	3/13	633	26.8	30.0
7	178	17.4			42	2.4	3/13	271	15.6	3/13	424	24.4	36.2
8	185	92.8	677	7.3	1,111	12.0	3/19	2,400	25.9	3/12	4,840	52.1	50.0
9a&b	196	G 83.0	3,674	44.2	1,440	17.4	3/21	11	.13	3/19	3,620	43.6	99.9
10	219	G153.0	816	5.3	1,097	7.2	3/19	5,090	33.3	3/19	7,180	46.9	29.2
11	234	30.0	1,652	55.1	683	22.8	3/18	0	0	3/18	2,040	68.0	100.0
12	236	x154.0	4,834	31.3	4,147	26.9	3/28	a3,030	19.7	3/18	15,600	101.3	80.6
13	250	45.8	1,560	34.2	1,284	28.0	3/27	a395	8.6	3/18	4,070	88.8	a100.0
14	256	17.2	675	39.2	400	23.3	3/18	0	0	3/18	915	53.2	100.0
15	261	16.5	180	10.9	210	12.7	3/20	254	15.4	3/12	762	46.2	66.8
16	272	38.0	0	0	14	.37	3/18	2,720	71.6	3/12	2,760	72.6	1.45

*—U. S. Geological Survey Water-Supply Paper No. 798.

x—Net drainage area.

G—Flow at U. S. Geological Survey gaging station downstream from dam.

a—No flood discharge required.

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At Outlet of Res. No.	Drainage Area Sq. Mi. (3)	Storage Capacity—Million cu. ft. Available at Beginning of Flood Total Per sq. mi. (4)			Used During Flood—Sept. 1938 Total Per sq. mi. (6)		Date (8)	Observed Peak Av. Daily Flow c.f.s. (9)		c.f.s./s.m. (10)	Date (11)	Estimated Peak Av. Daily Flow Without Storage c.f.s. (12)		c.f.s./s.m. (13)	Per cent Reduction of Peak Flows (14)
3	114	363	2,094	5.8	1,274	3.5	9/21	598	1.6	9/21	6,180	17.1	90.1		
8		92.8	598	6.4	211	2.3									
9	139-	G83.0	104.0	1.2	50	.6	9/21	1,350	16.3	9/21	1,440	17.4	6.2		
140															
10	159-	G153.0	340	2.2	719	4.7	9/22	4,030	26.4	9/22	5,000	32.6	19.4		
160															
11	178	30.0	417	13.9	422	14.1	9/22	669	22.3	9/21	2,340	78.0	71.5		
12	176	x154.0	1,632	10.7	1,642	10.7	9/22	10,768	70.0	9/21	12,500	81.2	13.9		
13a	189	45.8	478	10.4	471	10.3	9/21	2,040	44.5	9/21	4,760	103.8	57.2		
14	194	17.2	288	16.7	293	17.0	9/21	0	0	9/21	1,260	73.3	100.0		
15	202	16.5	68	4.1	205	12.4	9/21	1,130	68.5	9/21	1,940	117.6	42.0		
16	216	38.0	0	0	20	.53	9/21	3,140	82.7	9/21	3,210	84.5	0		
17	214	40.4	146	3.6	317	7.8	9/22	1,700	42.1	9/21	3,260	80.7	49.4		
18	222	18.0	1	.06	16	.9	9/21	2,130	118.3	9/21	2,140	118.9	0		
19	235-	G132	19.0	19.0	952	7.2	9/21	22	.2	9/22	3,280	24.8	99.4		
236															
20	239	1,044	17,680	16.9	4,360	4.2	9/24	3,220	3.1	9/23	15,000	14.3	78.6		
21	252-	375	1,562	4.2	1,867	5.0	9/24	4,480	12.0	9/23	12,500	33.3	64.0		
253															
22	257-	314	1,000	3.2	950	3.0	9/21	10,462	33.3	9/21	20,000	63.6	47.7		
258															
23	292	119	30	.3	134	1.1	9/22	1,690	14.2	9/22	1,740	14.6	2.9		
24	300	90.4	171	1.9	393	4.3	9/23	841	9.3	9/22	2,730	30.1	69.2		
25	320	34.4	1.3		18.2	.5	9/21	1,280	37.2	9/21	1,396	40.6	8.3		
26	344	228			535	2.4	to 9/26	a0	0	—	—	—	a100.0		
27a	345&L	118	1,037	8.8	593	5.0	to 9/26	a0	0	—	—	—	a100.0		
27b	L						to 9/25	a0	0	—	—	—	a100.0		
28	374-	109	2,781	25.5	465	4.3	9/23	1,180	10.8	9/21	3,900	35.8	70.0		
	375														

*—U. S. Geological Survey Water-Supply Paper No. 867.

x—Net drainage area.

G—Flow at U. S. Geological Survey gaging station downstream from dam.

L—Letter.

a—No flood discharge required.

reservoirs, among them Sebago Lake, Lake Winnepesaukee, Scituate Reservoir, and Mascoma Reservoir system, where more storage was used than was available in their rated capacity. This additional storage was temporary storage above the spillway crest resulting from the rise of water level above this crest, necessary to pass water over the spillway. In the case of Lake Winnepesaukee, during the 1936 flood, this represented the use of 9009 m.c.f. of storage where only 7700 m.c.f. was available below the spillway. This above-spillway storage is equal to 18% of the available storage. Because of the larger water surface area of these reservoirs, this temporary storage was considerable and produced a substantial reduction in the estimated peak flow.

Another beneficial factor was the delay which was made in the time the peak flow passed the storage dam. This delay in time amounted to several days and resulted in flood control benefits from the reservoir considerably greater than those indicated by the per cent reduction in peak flows (Column 14). In these cases very little water was being spilled at the time of the natural peak and the amount spilled gradually increased while the flow from the uncontrolled areas downstream decreased. This resulted in a definite reduction of flood flows at points downstream from the reservoir approaching in amount the natural flood peak at the storage dam. The time of duration of high flows at downstream points was somewhat increased but this would not increase flood damage, because once a building is inundated, no additional damage is incurred by extending the time of inundation a short additional period. Due to this delay in time of peak, flood benefits were experienced at points downstream nearly equal to that which would have resulted had all the flood waters above the reservoir been stored. This major benefit was experienced even though Column 14 indicates only a minor reduction in flood flow.

The computed per cent reduction of average daily flood flow has been plotted against the storage capacity used in the floods of March, 1936, and September, 1938, Fig. 18. The enveloping curve indicates the minimum amount of reduction in peak flow which can be expected from having various amounts of storage capacity available in case of a flood of the intensity of 1936 and 1938 at their maximum flow. The points actually observed are located below this line the extent below depending on the intensity of the flood in the particular area in which the reservoir was located. The two points which fall above this line

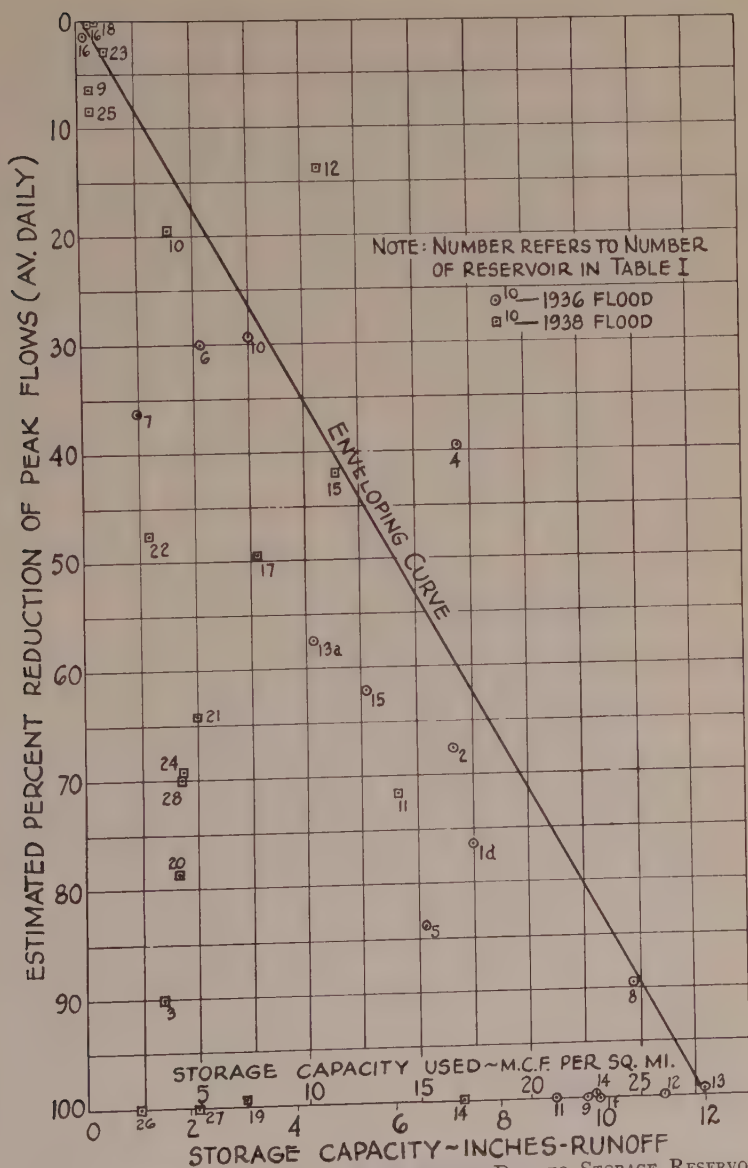


FIG. 18.—REDUCTION OF PEAK FLOOD FLOWS DUE TO STORAGE RESERVOIRS.

are "sports" and though they appear to be correct, probably have something wrong in the available data not definitely apparent.

It is to be noted that the peak flows given in the tables are the average daily flows and that instantaneous peak flows much larger than these occurred during the floods. There was not a sufficient number of cases where instantaneous peak flows were available to permit a study of the effect on their magnitude from existing reservoirs. The per cent reduction of these peak flows because of their short duration would be considerably more than the results given in the tables obtained by using the average daily flow. The values arrived at can, therefore, be considered as conservative.

CHAPTER V

Flood Runoff Analysis

FLOOD HYDROGRAPH AND THE BOSTON SOCIETY OF CIVIL ENGINEERS' FLOOD FORMULA

THE significance of the flood hydrograph in the analysis and prediction of flood runoff and peak flows was first noted in the report of this Society's Committee on Floods, September, 1930,¹ which called attention to the fact that the base of flood hydrographs at any point on a stream, for storms within the "concentration period", had substantially the same length regardless of the amount of runoff, so that the flood peak varied with the total flood runoff. From this there was derived a formula

$$Q = C_f R \sqrt{A}$$

where Q = cu. ft. per second, peak flow

R = the flood runoff, in inches

A = drainage area, in square miles

C_f = a flood coefficient for each location.

A "unit" flood characteristic curve was also derived, which put the hydrographs of floods for any given location on the basis of one square mile drainage area and 1-inch flood runoff. The peak of this flood characteristic curve gives the flood coefficient C_f . Since that time, the analysis of floods, through the use of the flood hydrograph, has been the subject of continuous study, which has brought it to a high degree of effectiveness for use in the design of spillway capacities and flood control and prevention works. The following discusses briefly the successive steps in this study.

The Boston Society report was followed about eighteen months later by the description of the unit hydrograph² and the distribution graph,³ which have been in constant use since and have proved most useful tools. Where the Boston Society's flood characteristic curve was based on all floods within the concentration period, the unit hydrograph is based on a flood due to a storm of one day's duration reduced to 1" runoff, and hydrographs for storms of more than one day's

¹References in this section refer to the bibliography shown on page 85.

duration are obtained by adding together successive unit hydrographs spaced at intervals of one day. This gives it a wider application for floods from storms of various durations. The distribution graph, derived from the unit hydrograph, was based on the percentage of the flood occurring during each period of time. As the unit hydrograph was generally on a daily basis, the distribution graph was also taken on a daily basis. The distribution graph would give a curve that more nearly followed the actual flood hydrograph, if the time intervals were taken shorter.

In some ways the Boston Society flood characteristic curve appears to be better expressed than the unit hydrograph, particularly for use in comparing different areas. Both curves are made up for a unit of one inch runoff; the vertical scale of the unit hydrograph thus gives flows for a one-inch runoff, but the horizontal scale is based on the actual time for the drainage area in question; whereas the Boston Society curve reduced both the flow and the time to a unit drainage area of one square mile.

The flood characteristic curve of the Boston Society, the unit hydrograph and the distribution graph are thus simply different expressions of the flood hydrograph. Mr. L. K. Sherman, in his discussion of the distribution graph,⁴ called attention to the fact that the unit hydrograph could be converted to the distribution graph by simply changing the vertical scale. In the same manner the unit hydrograph is converted to a flood characteristic curve by dividing both the horizontal and vertical scales by the square root of the drainage area. Fig. 19 is a reproduction of Fig. 18 from the Boston Society's 1930 report, giving characteristic flood curves for several different floods on the Merrimack River at Lowell. To this has been added the characteristic curves for the 1936 and 1938 floods, and also the appropriate horizontal and vertical scales for conversion to unit hydrographs and distribution graphs.

The distribution graph scale has been based on using one day periods. Using 12 hour periods would reduce the scale by one-half, and 6 hour periods by one quarter. This changing of the vertical scale, due to the length of period assumed, would appear to seriously affect the usefulness of the distribution graph in making a comparison of different drainage areas. One particular advantage of the flood characteristic curve is that its peak gives the Boston Society's flood coefficient C_f in flood formula $Q = C_f R \sqrt{A}$. It gives a direct measure

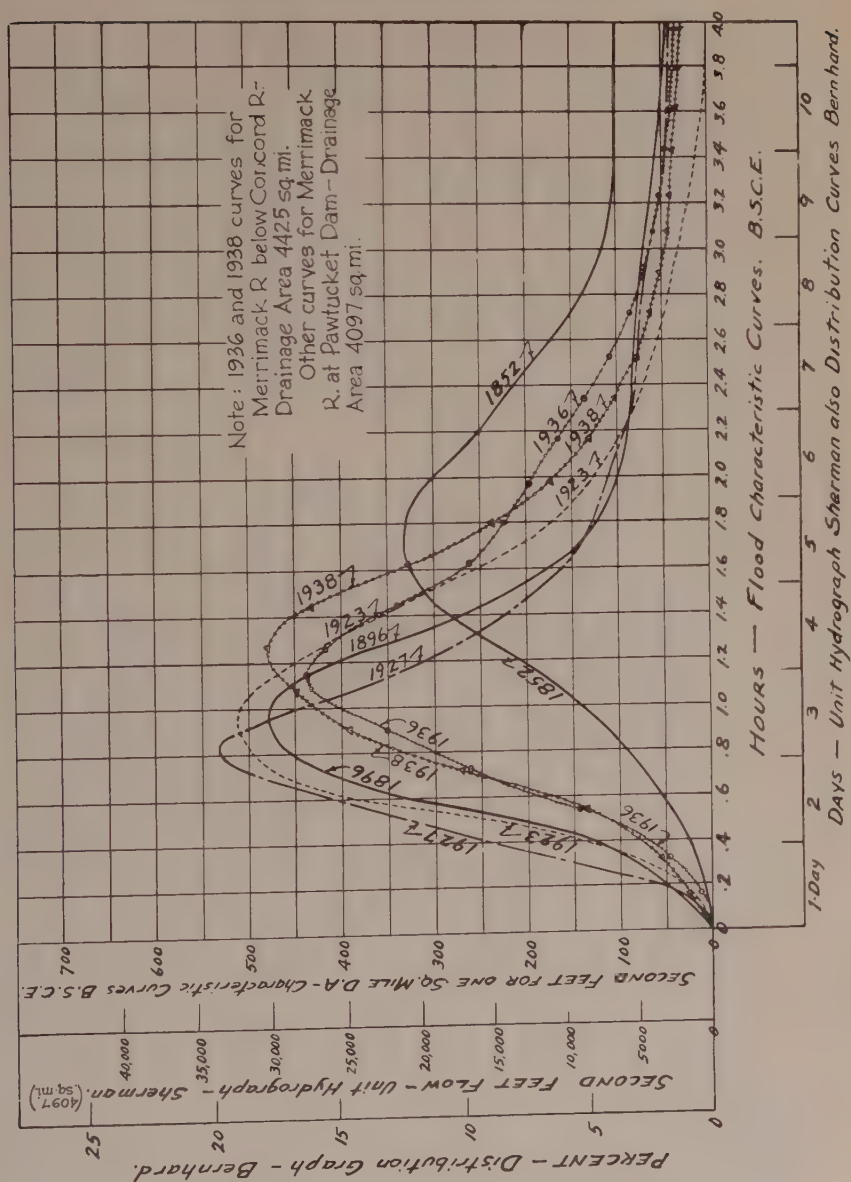


FIG. 19.—FLOOD HYDROGRAPHS OF THE MERRIMACK RIVER AT LOWELL WITH SCALES FOR CONVERSION TO UNIT HYDROGRAPH AND DISTRIBUTION GRAPH.

of the flood producing characteristics of the watershed above the point where the hydrograph was obtained. The peak of the unit hydrograph divided by the square root of the drainage area will, of course also give flood coefficient C_f .

The particular advantage of the unit hydrograph method would seem to be its technique in making possible the derivation of floods due to storms exceeding the concentration period in duration. Fig. 20 shows the application of the unit hydrograph method to the 1927 flood at Lowell, which was caused by a storm of short duration. Similar storms at one day intervals were assumed with the hydrographs worked out and reduced to a one-inch total flood runoff in each case. The similarity between this group of curves and those shown in Fig. 19 is apparent. The flatter curves in the latter were those produced by the longer storms.

Other analyses of the flood hydrograph have been made. R. T. Zoch⁵ in September, 1934, published one of a series of papers giving general equations of the flood hydrograph in terms of rainfall, rainfall duration, time of concentration, i.e. time of transit of the water from the furthest point of the drainage area to the point of measurement, and a constant representing the water withheld from running off by infiltration, surface detention and channel storage. This consisted of a series of equations dividing the flood hydrograph into various and significant periods, from the beginning of the rain to the final end of the runoff. The fourth of these periods is the period after the water from the rain at the end of the storm has reached the point of measurement. His equation for the flow during this period is the equation for the recession curve of the hydrograph, assuming that the proportion of the total rain withheld is a constant.

The significance of the point of inflection of the curve of the hydrograph after the peak was pointed out by Mr. R. E. Horton,⁶ this portion of the curve representing purely drainage from water withheld. Mr. Horton derived curves of channel storage vs. outflow from the recession curve of the hydrograph of a small drainage area, and used them to correct the original hydrograph for the effect of the channel storage.

Another analysis of the hydrograph was given in a paper by Otto H. Meyer,¹⁰ in which he derived hydrographs for curves of various lengths up to the time of concentration and beyond. According to this analysis, the hydrograph of a storm equal to the time of concentration would have a sharp break in the recession curve at that time. For

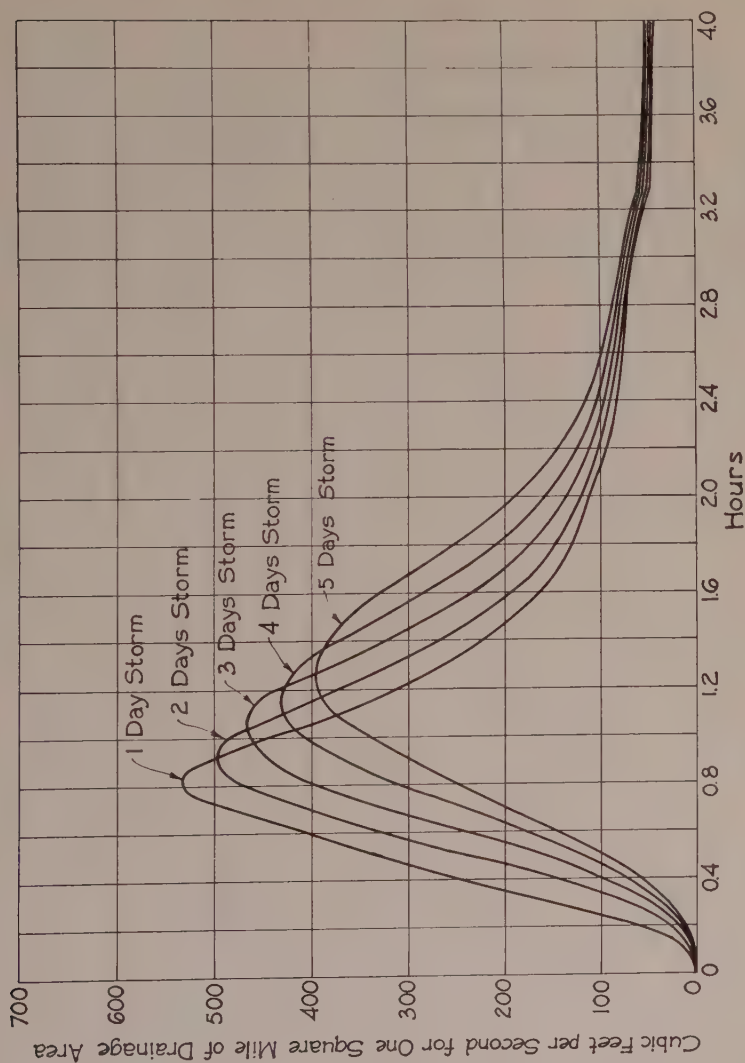


FIG. 20.—CHARACTERISTIC FLOOD CURVES FOR ONE- TO FIVE-DAY STORMS IN MERRIMACK RIVER AT LOWELL, MASS. BASED ON UNIT-HYDROGRAPH METHOD WITH 1927 FLOOD AS BASIS,—ONE-INCH FLOOD ON ONE SQUARE MILE DRAINAGE AREA.

storms longer than the concentration time, the hydrograph would have a flat top extending for the length of the storm and then the sharp break to the recession curve.

A recent analysis by Turner and Burdoin,¹¹ (undertaken originally for this Committee but published as a separate paper) uses the recession curve to derive a storage vs. outflow curve. The examples show a similar storage curve for all floods at a given location, Fig. 21. An inflow runoff hydrograph, that is, a hydrograph of the runoff of a given flood, at the point of measurement, without any storage effect, is then derived, based on the duration of the rainfall, t_o , and the concentration period, $\frac{L}{V}$, where L is the distance to the farthest point on the drainage area and V the velocity of travel. Assuming a uniform rate of rainfall and a rectangular drainage area, this inflow hydrograph is shown to be as follows, Fig. 22: for a storm shorter than the concentration period, $t_o < \frac{L}{V}$, a rectangular trapezoid with a base equal to $\frac{L}{V} + t_o$ and a top equal to $\frac{L}{V} - t_o$; for a storm equal to the concentration period, $t_o = \frac{L}{V}$, a triangle with a base equal to $2 \frac{L}{V}$; for a storm longer than the concentration period, $t_o > \frac{L}{V}$, a trapezoid with a base equal to $\frac{L}{V} + t_o$ and a top equal to $t_o - \frac{L}{V}$. Assuming such an inflow runoff hydrograph, plus the base flow, as the inflow to the point of measurement, it is routed through the storage by the regular flood routing process to obtain the outflow hydrograph corrected for storage, that is, the actual flood hydrograph. Examples are given from actual flood hydrographs for different floods on the Connecticut, Figs. 23 and 24, and Merrimack Rivers with close agreement between the computed hydrograph and the actual one. Using this method, a series of typical flood hydrographs, without the base flow, is worked out for a fictitious example, showing the effect of varying t_o , the amount of storage, and $\frac{L}{V}$, Figs. 25, 26, and 27. The paper compares the method above described with Zoch's⁵ theoretical equations. If the

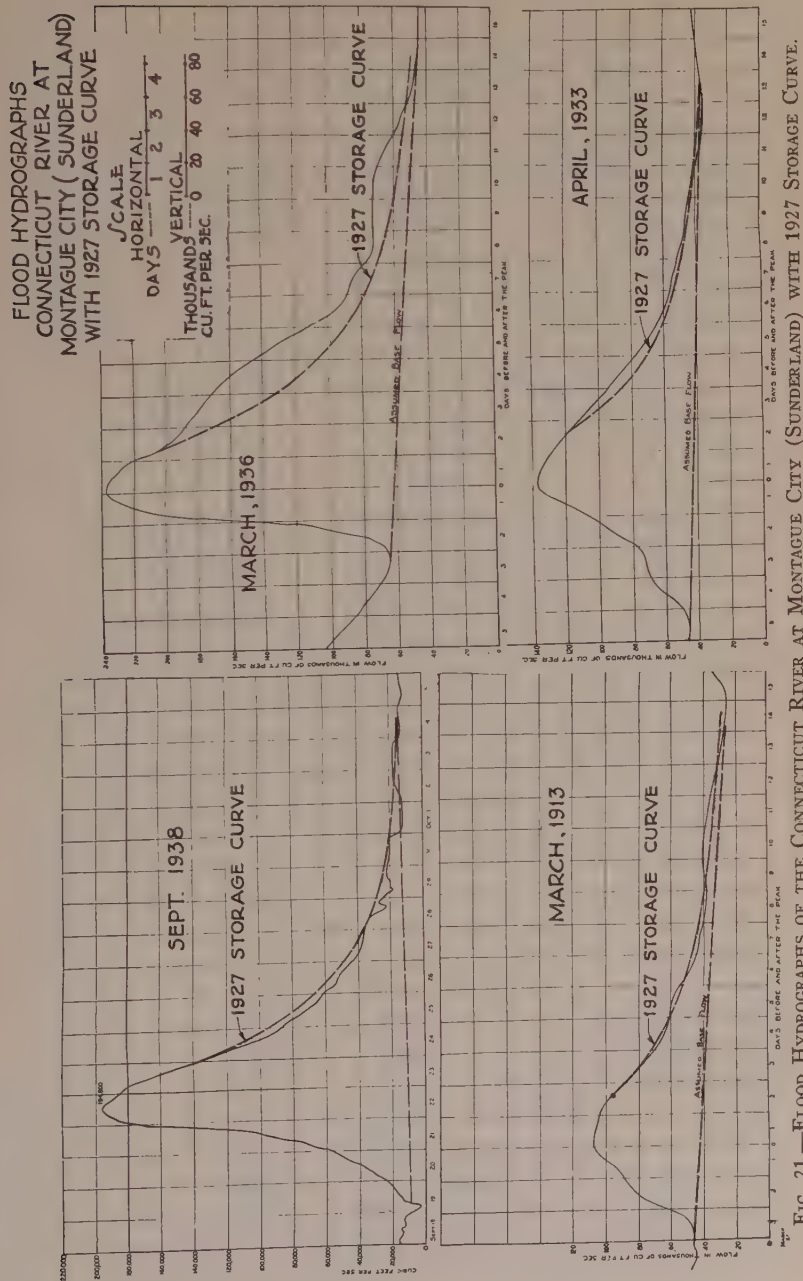


FIG. 21.—FLOOD HYDROGRAPHS OF THE CONNECTICUT RIVER AT MONTAGUE CITY (SUNDERLAND) WITH 1927 STORAGE CURVE.

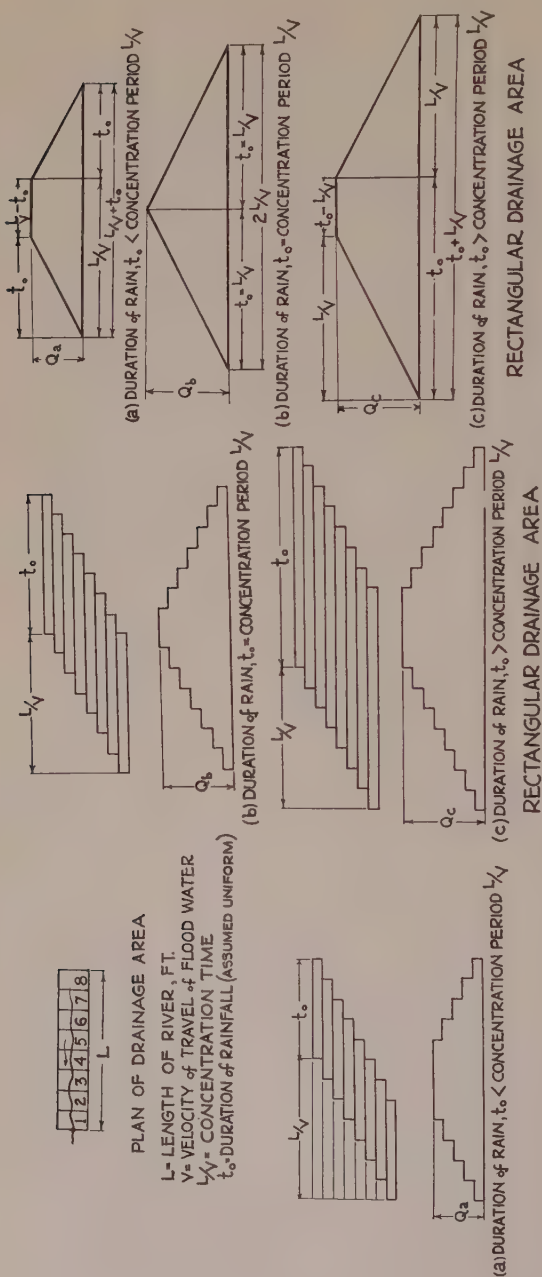


FIG. 22.—DIAGRAMMATIC FLOOD RUNOFF INFLOW HYDROGRAPH.

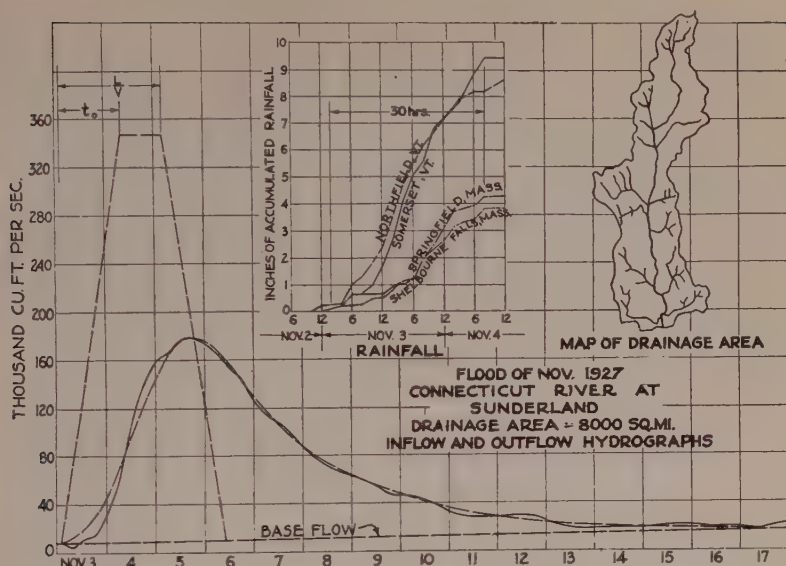


FIG. 23.—CONNECTICUT RIVER AT SUNDERLAND. FLOOD OF NOVEMBER, 1927.

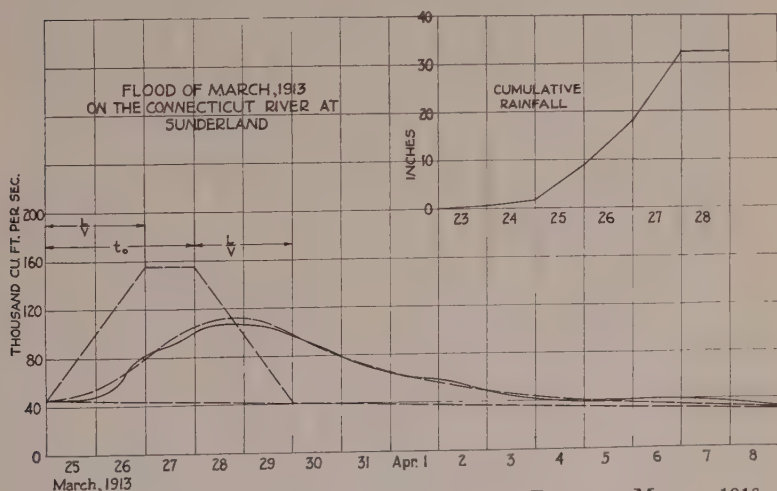


FIG. 24.—CONNECTICUT RIVER AT SUNDERLAND. FLOOD OF MARCH, 1913.

base flow is eliminated and his constant for the proportion of the rainfall withheld in infiltration and storage is made to apply to storage only, and the same constants are used, his general equations give the same curve.

A comparison of this method with the unit hydrograph shows that if the base flow is eliminated or assumed as a straight level line for the duration of the flood and the storage vs. outflow curve is a straight line, this analysis will give the same results as the unit hydrograph, i.e., for a storm of one day's duration and 2-in. runoff it will give twice that of 1-in. runoff. A two days' storm of a total of 2-in. runoff will give the same hydrograph as the sum of two unit hydrographs spaced one day apart. With varying base flows and storage curves that are not straight lines, the results to be expected would probably differ slightly from hydrographs made up by the unit hydrograph method.

This method of analysis should be carried further in order to determine its applicability to streams of different sizes and shapes and, if feasible, rainfalls of varying intensities. It certainly appears to account thoroughly, as do Zoch's equations, for the characteristic shape of the normal flood hydrograph, and to present a method whereby the effect of the different elements entering into a given flood hydrograph may be analyzed.

In summarizing the flood history of the New England streams, the 1930 Report of the Boston Society Committee on Floods¹ gave the following statement (page 298):

" It appears that the 1927 flood had a concentrated storm run-off of between 3 and 6 inches in those areas where the greatest damage was done. Most of the streams of New England have had an occasional flood run-off of between 3 and 4 inches. The only case where the concentrated run-off has exceeded 4 inches during the previous 50 years was the 1923 flood on the Penobscot River, when the figure reached about 5.5 inches, due, however, partly to melting snow. The Miami River, in the great flood of 1913, had a flood run-off of 8 inches. It further appears that a flood run-off of between 3 and 4 inches occurs about once in 50 years in New England. Such floods usually cause a great deal of inconvenience and considerable damage, but do not generally assume the proportions of a catastrophe. Apparently, most of the river channels and structures are taxed severely by the occasional 3 to 4 inch flood, but can usually be counted upon to come through without great damage. Floods producing a flood run-off of 6 inches and over in New England will inevitably overtax the capacity of river channels and cause great loss. The amount of damage and the loss of life will depend entirely upon the local conditions."

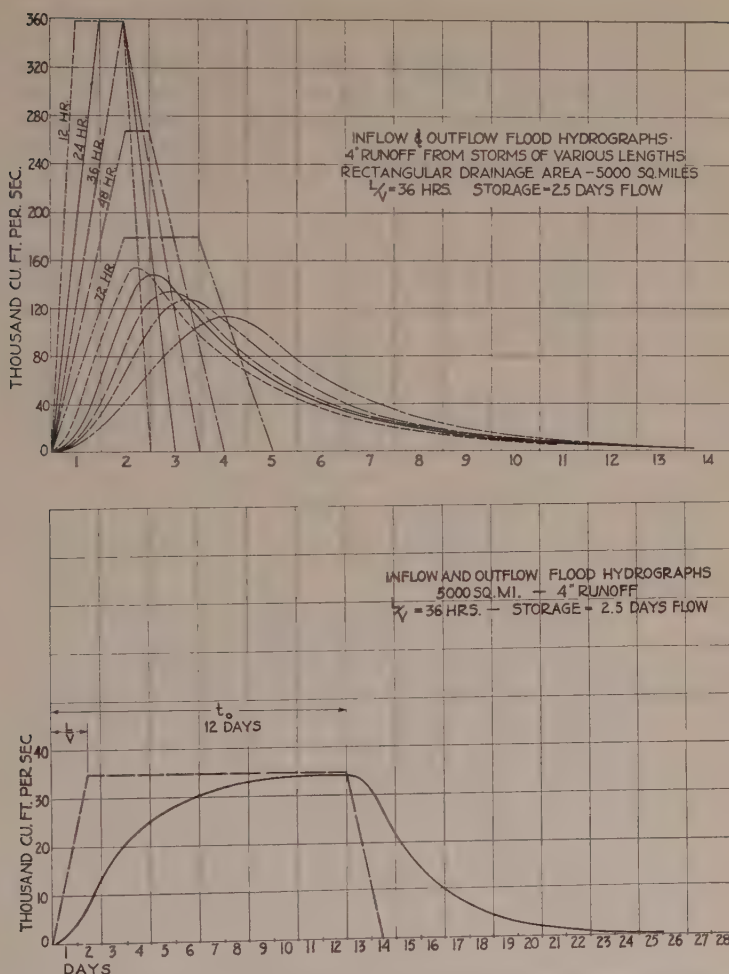


FIG. 25.—FLOOD INFLOW AND OUTFLOW HYDROGRAPHS WITH STORMS OF VARIOUS LENGTHS, t_o .

The March floods of 1936 together gave a total runoff of ten to twelve inches from many New England streams. The period of flood flows was prolonged much beyond the concentration period, and a study of the flows shows an equivalent concentrated storm runoff of between 5.5 and 6.0 inches for certain portions of the Connecticut, Merrimack and Androscoggin Rivers. The lower part of these rivers experienced floods comparable to the 1923 flood on the Penobscot

River, and to the 1927 floods on some of the Vermont streams. The hurricane flood of 1938 produced similar flows on some of the Connecticut and Thames Rivers tributaries in Massachusetts and Connecticut. These two great floods considerably extended the area of New England that has experienced floods approaching 6 inches of equivalent concentrated flood runoff. The probabilities of recurrence during the next fifty years are very remote, but as was stated in the previous report, even an 8 inch flood cannot be considered an impossibility. This would mean an increase of one-third above the disastrous floods of recent experience.

It is now eleven years since the 1930 report of this Society's Committee on Floods called attention to the fact that a hydrograph of a flood, at a given point on a stream, was the best measure of its flood producing characteristics. These eleven years have seen development of methods of analysis of flood hydrographs based on this, by

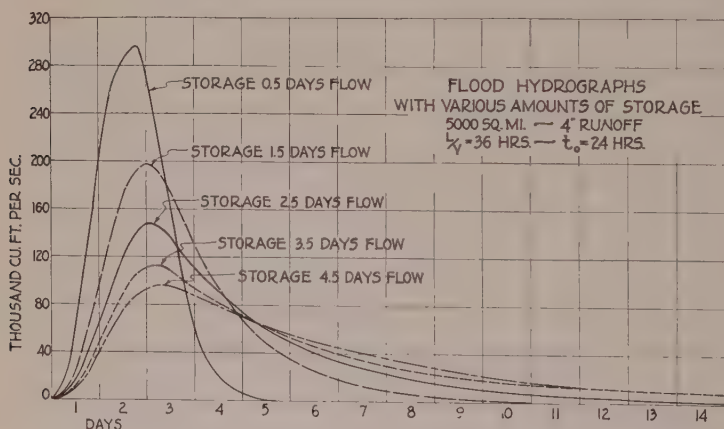


FIG. 26.—FLOOD HYDROGRAPHS WITH VARIOUS AMOUNTS OF STORAGE.

which anticipated floods for various assumed conditions of rainfall can be predicted with considerable accuracy. This modern flood analysis, based on the hydrograph, has served to emphasize the difference in flood producing capacities of rivers at different locations, which is shown by their different flood characteristic curves or unit hydrographs. While graphs and formulae expressing maximum floods to be expected, based on the drainage area alone and generally expressed in cu. ft. per sec. per sq. mi. of drainage area, are useful for general

purposes and for checking of other determinations, their use for a given problem may give results considerably in error, unless a coefficient is included which takes into account the flood producing characteristics of each particular point on a river.

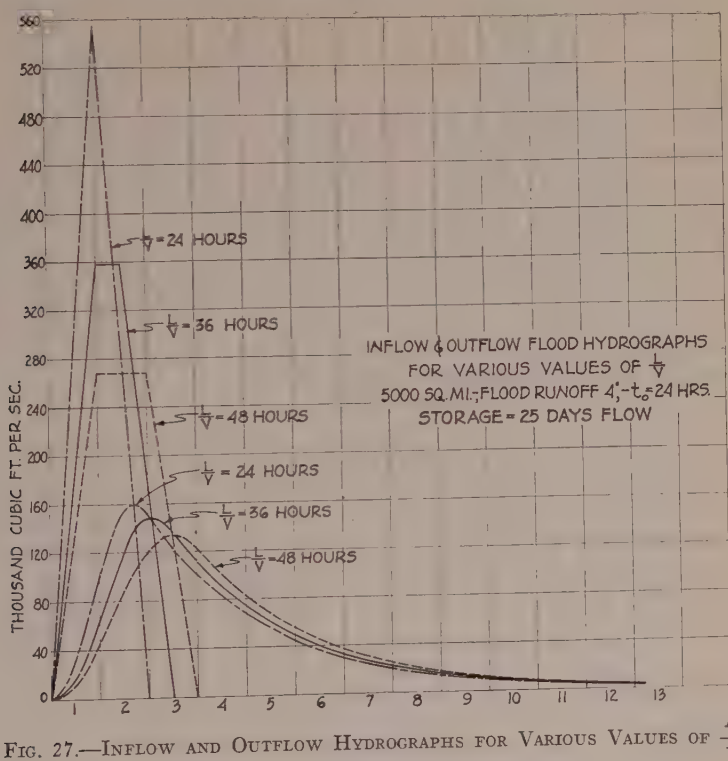


FIG. 27.—INFLOW AND OUTFLOW HYDROGRAPHS FOR VARIOUS VALUES OF $\frac{L}{V}$.

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FLOOD ROUTING

In the 1930 Flood Committee Report there was some discussion of channel storage and its effect on the flood peak at various points in the river. Since that report was published a method of routing of floods through a reach of river has been perfected.⁹ This is based on the general storage equation:

$$\frac{t}{2} O_2 + S_2 = \frac{t}{2} (I_1 + I_2) + S_1 - \frac{t}{2} O_1$$

Where

I_1 and I_2 = the inflow at the beginning and end of each period, t .
 O_1 and O_2 = the outflow at the beginning and end of each period, t .
 S_1 and S_2 = the storage volume corresponding to O_1 and O_2 .

This relation may be modified for rising and falling stages by considering a wedge of storage above the river surface on the basis that the storage consists of two parts, a "prismatic" storage below the normal slope in the stream, plus or minus "wedge" storage due to the changing slope whether the river is rising or falling, this wedge storage being added to the prismatic storage in case of a rising river and deducted from it in case of a falling river stage. Flood routing analysis has been checked many times with actual hydrographs and

actual storage, so that within limits any problem involving the routing of a flood or summation of various floods through given stretches of river, where the storage is known, may be solved with considerable confidence in the correctness of the answer. This has proved of great importance in the analysis of the effect of a system of flood control reservoirs on the flood reduction in the main rivers.

SPILLWAY DESIGN FLOODS

The Boston Society's 1930 report¹ had a general statement on the size of floods for which spillways of dams should be designed. This discussion was generally based on the assumption that the peak flow would be determined by some formula generally expressed in c.f.s. per square mile of drainage area. The Boston Society formula went somewhat further than these former peak formulae, and rated floods at different points by the application of a flood coefficient based on an analysis of previous hydrographs; the formula also permitted the flood peak being fixed in proportion to the total flood runoff. Figures were given for the flood runoff that might be expected at varying frequencies with a probable maximum at 8". For spillway design floods the report cited the difference in the character of river structures as modifying the flood for which the spillway should be designed. It also stipulated that the storage capacity above the spillway level might be counted on in reducing the maximum peak flow.

The increased attention devoted to the estimated flood to be expected at a given point on a stream, which was first allowed for by the Boston Society formula Flood Coefficient, has changed this whole question of design floods. The unit hydrograph method has permitted a much more scientific determination of the flood that may be expected at any point for a given storm rainfall, and of the effect of storage above the dam. Limiting figures of maximum runoff per square mile of drainage area, based on enveloping curves of floods all over the country, are used more as a check than for any other purpose.

With the use of maximum possible storm rainfall, assuming a high percentage of runoff and also a large amount for runoff from melting snow, it is possible to estimate very high peak discharges for spillway design floods. If to the depth required over the spillway are added freeboard for wave action and frost on earth abutments, there is perhaps a tendency to reach a size of spillway that may be prohibitive in cost for any but the very largest structures paid for by

public funds. While it is certainly advisable to know the absolute limit which nature may reach when all the maximum conditions are added together, there may be a question in many structures whether such safety is necessary or advisable. Some of the maximum peak floods, reached by this type of analysis, are of such a quantity that there would be few structures left in the whole river valley were they ever attained, and the failure of a river dam would add but little to the total destruction which would be caused. Like many other engineering problems, the exact figure to use for the design of a given structure will depend on its importance and cost and on the effect of its failure. Important structures for storage reservoirs, impounding very large bodies of water require a high degree of safety, whereas other structures perhaps on the same river, impounding smaller amounts of water, may not justify anywhere near such extreme values.

The floods of 1936 and 1938 exceeded the spillway capacities of many dams, but prompt action on behalf of the operators saved all but a few of the structures from failure. In general, it seems to have been the policy of most water power owners, after these floods, to change their structures so that a repetition of equally high water would not damage them. This is quite different than would be the case, if the maximum possible flood were assumed to be that for which the structure should be designed.

The previous report devoted considerable space to a discussion of river structures and structures along the river banks. This lesson is a hard one to learn, and many of our New England streams suffered during the 1936 and 1938 floods from encroachment of bridges and buildings on the normal flood channel. In many such places the structures were destroyed by the flood, and in various flood control or flood improvement projects, and in the rebuilding of many of the bridges, adequate waterways based on past experience have been provided, so that in effect a good deal of the rebuilding has actually been in the way of flood betterment. Some special projects, among them that at Fitchburg, Mass. on the Nashua River, and at Orange and Athol on the Millers River, have made definite improvements and removed encroachments on the river channel. Continual watchfulness, on the behalf of authorities, is required to prevent the construction of work in the rivers that will obstruct the flood channel, particularly

if many years go by without a large flood and the memories of the three recent floods fade into the past.

RAINFALL-ALTITUDE RELATIONS

1927 Flood

In the Report of the Flood Committee of September 1930¹ a study of the storm rainfall for Nov. 2-5, 1927 and altitude for Vermont stations showed as an approximation the relation:—

$$P = 6.6 + (E-5) \times 0.18$$

Where P = Storm rainfall in inches
 E = elevation in hundreds of feet

1936 Flood

A similar study for the period March 9-22 incl., 1936, for stations in the Connecticut River Basin shows an approximate relation:—

$$P = 6.2 + (E-5) \times 0.14$$

For the Merrimack River Basin:—

$$P = 8.2 + (E-5) \times 0.35$$

For New England as a whole:—

$$P = 6.2 + (E-5) \times 0.17$$

It should be kept in mind that these are only very generalized relations and individual stations show wide departures from them. They appear to indicate, however, a general approximate pattern indicating the usual tendency of great storm rainfall to increase with elevation here in New England.

1938 Flood

The "hurricane flood" of September 20-21, 1938, based upon similar plots, appears to be somewhat inconsistent with the foregoing

¹Journal Boston Society of Civil Engineers, Sept. 1930, Vol. XVII, No. 7, page 305 and Fig. 2a.

relations, with rather variable effects of elevation upon storm rainfall. This is probably due to the type of storm, the unusual rate of hurricane movement and high wind velocities. Apparently it proceeded northerly through New England, with the greatest rainfalls in the general path of the hurricane, affected somewhat by changes in land elevation.

C. M. Saville* made a study of rainfall-altitude relations, plotting observed results along the "path of greatest rainfall intensity" for the hurricane storm including 9 stations between Stafford, Ct. and Wilton, N. H., and deduced the relation:—

$$P = 11 + (E-5) \times 0.7$$

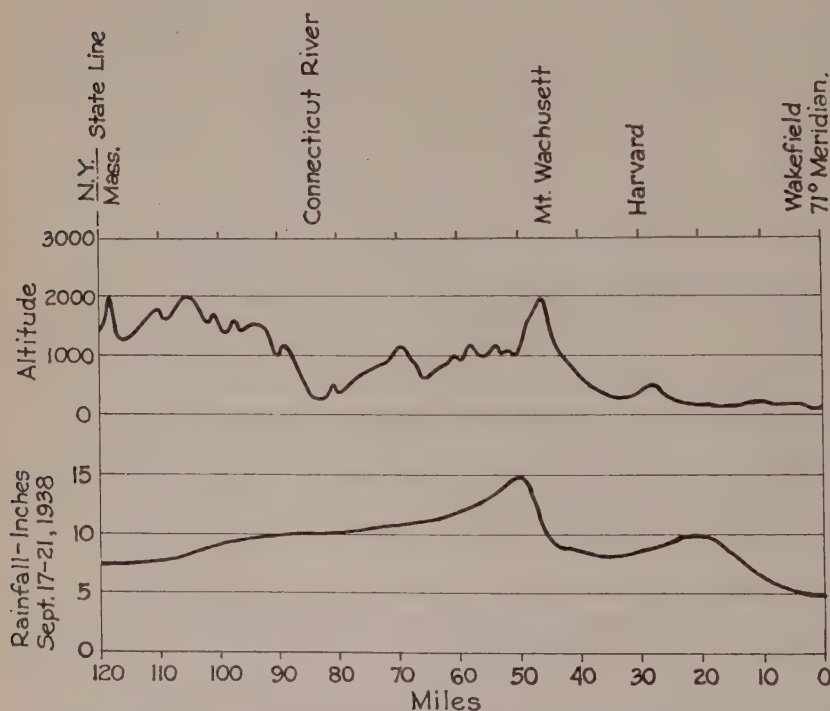


FIG. 28.—STORM OF SEPTEMBER, 1938. SECTION EAST AND WEST ALONG 42°-30' PARALLEL.

This curve is fairly well defined by the data and represents variation in maximum rainfall with elevation.

Profiles have been plotted of land elevation, with corresponding storm rainfall. The profiles running northerly through New England show no definite relation between the two factors. The profiles running from east to west through central Massachusetts do show higher rainfall near the general vicinity of Mt. Wachusett, consistent with higher elevation, but in western Massachusetts, with similar elevation to those near Mt. Wachusett, storm rainfall was materially less, Fig. 28. Similar profiles east and west through the White Mts. and northern Vermont show little or no elevation effect. Profiles east and west through central Connecticut and Rhode Island show maximum

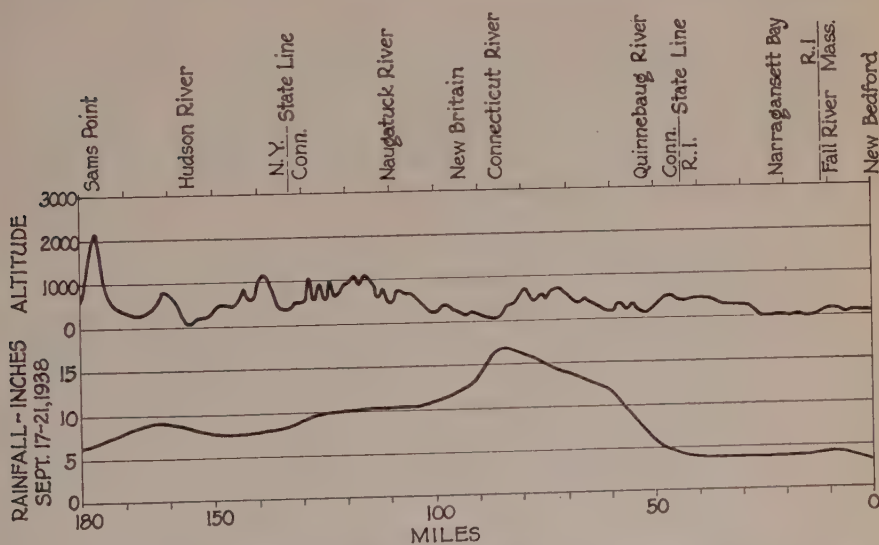


FIG. 29.—STORM OF SEPTEMBER, 1938. SECTION EAST AND WEST ALONG 41° - $40'$ PARALLEL.

rainfall in the general vicinity of the Connecticut River Valley and no definite correlation with altitude, Fig. 29.

Charles F. Brooks¹ states the following with reference to the hurricane rainfall:—

¹"Hurricanes into New England", Charles F. Brooks—The Geographical Review, Jan. 1939, p. 125-6.

"As the hurricane entered the trough it traveled along the general N-S. front between the tropical air on the east and the modified polar air 20 degrees cooler on the west. The rapid rotation began to turn the fronts; the warm front, originally toward the northeast, turned toward the north; the cold front, originally toward the south, turned toward the east, as the storm passed over New England. As the tropical air passed up the warm front slope, its fairly stable lapse rate was increased, and the increased rate resulted in deep convective overturning and extraordinarily heavy rains amounting to 4 to 6 inches or more over the central and western highlands of New England. These amounts, added to the 8 to 11 inches that had fallen in the preceding 4 days, gave 5-day totals of as much as 17 inches and resulted in record floods."

While elevation had some effect upon rainfall, as noted by Dr. Brooks, rainfall was apparently dominated by the more important factors of the hurricane characteristics and effects.

The committee urges the establishment of more precipitation gages at high altitudes located so as to give more accurate data of actual precipitation over whole drainage areas.

Snowfall-Altitude Relations

Comprehensive determinations of snow depth and water equivalent have been made in the Upper Merrimack River Basin, including Pemigewasset and Winnepesaukee basins, for the winters of 1938-9 and 1939-40 by the Public Service Company of New Hampshire. In Figs. 30 and 31 are plotted these relations for observations made March 17-19, 1939 and March 11-14, 1940, respectively. As will be noted, these plots both show a very definite and fairly regular increase in snow depth as well as water equivalent with elevation, and indicate the possibility of using a few index observation stations as a means of determining approximately the amount of snow on the ground in these basins and its water equivalent at a given time. Water equivalent as a per cent of snow depth is also shown by curves in the upper left portion of Figs. 30 and 31. There appears to be no definite relation between water equivalent as a per cent and altitude. Further study and analysis of the foregoing relations are desirable.

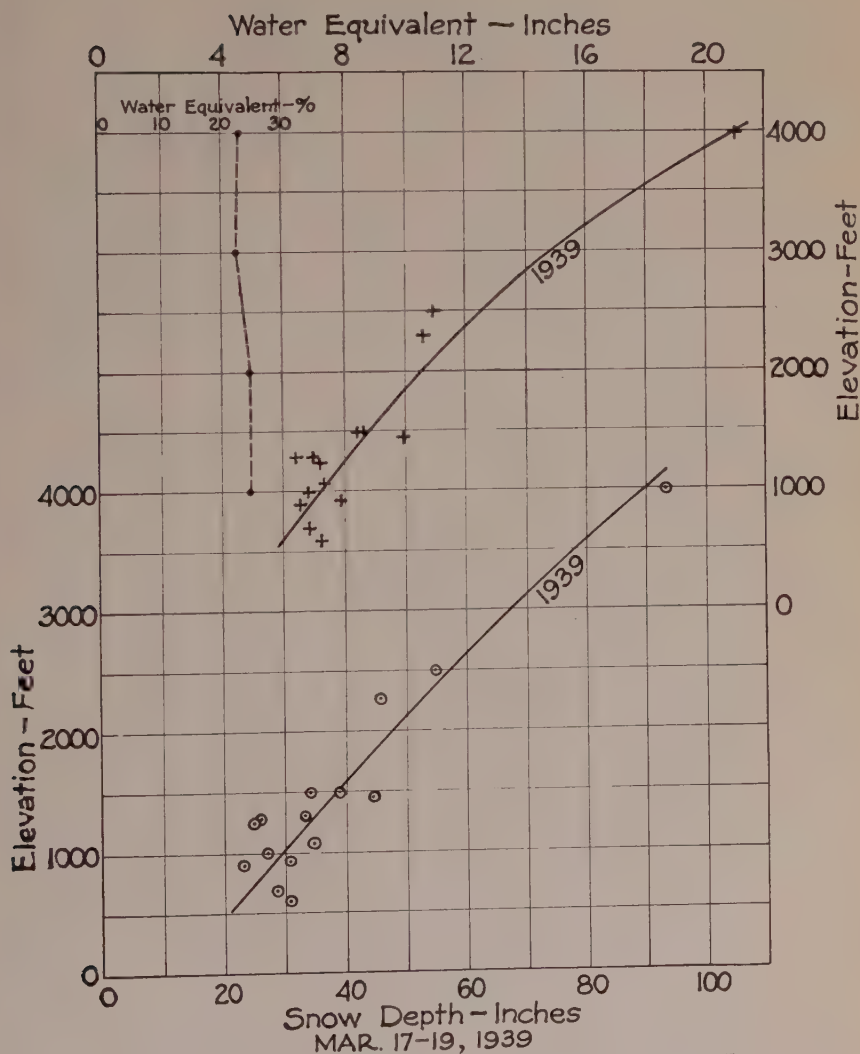


FIG. 30.—SNOWFALL-ALTITUDE RELATIONS IN THE PEMIGEWASSET AND WINNEPESAUKEE BASINS ON MARCH 17-19, 1939.

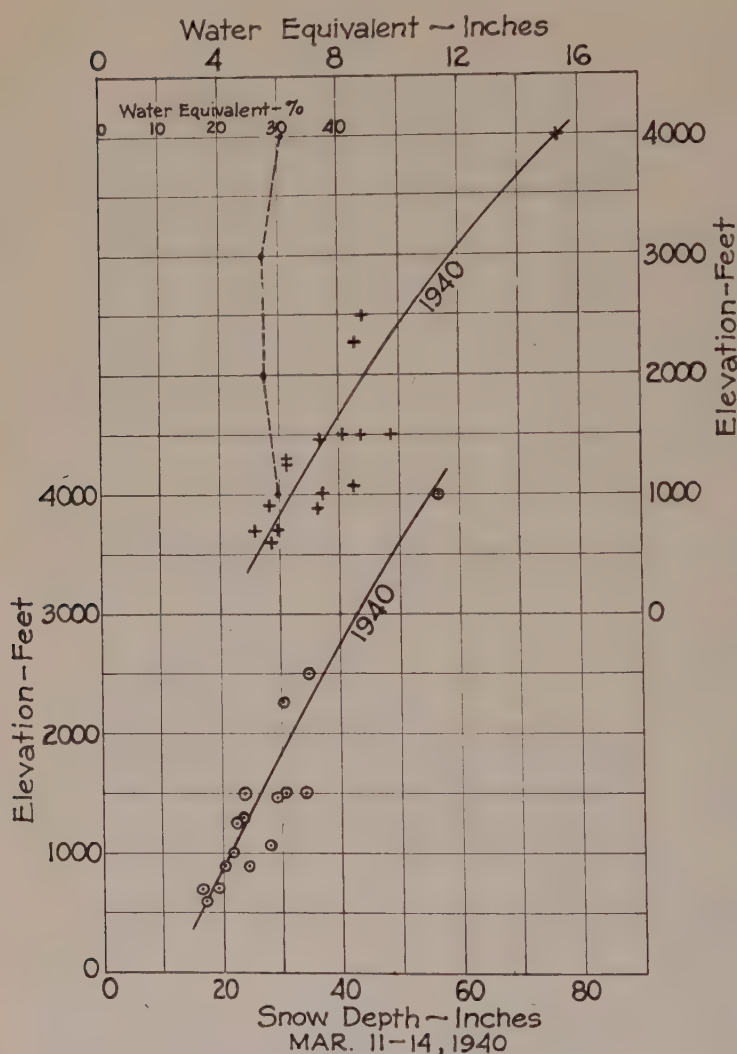


FIG. 31.—SNOWFALL-ALTITUDE RELATIONS IN THE PEMIGEWASSET AND WINNEPESAUKEE BASINS ON MARCH 11-14, 1940.

RUNOFF FROM MELTING SNOW

In the 1930¹ report of the Boston Society of Civil Engineers Committee on floods it was stated that there was but little information available upon the effect of snow accumulation on flood flows in

¹Journal Boston Society of Civil Engineers, Sept. 1930, Vol. XVII, No. 7, p. 354.

New England. At the present time after eleven more years have passed, during which the greatest flood of record in New England occurred with an unusually heavy snow cover on the ground at its beginning, there is still little knowledge of the exact effect of snow on rate of runoff. The need for this information in the design of flood control reservoirs as well as dams, bridges and other structures subject to winter flood and ice hazards is obvious.

In the past the U. S. Weather Bureau has collected data on the depth of snow as it fell at the various coöperative stations, but as the water content of snow on the ground was not measured and the density of snow varies widely, this information cannot be relied on to give an accurate estimate of snow water available for runoff. Within the past three years the Weather Bureau and the Geological Survey have been collecting data on water content of snow accumulations in New England which should be valuable for future use after information sufficient for monthly and yearly comparisons has been collected.

Because of their interest in snow water available for filling reservoirs and maintaining river flows, the employees of large water power companies and those in charge of municipal water supplies have collected much valuable data on water content of snow accumulation over a considerable period of years, but data on the rate of snow depletion and the resulting contribution to the rate of stream runoff, as well as the percentage of snow water which becomes runoff, are scarce.

As stated in the 1930 report referred to above, floods due to melting snow alone are rare and usually occur over limited areas. For this reason and due to the fact that most of the data available on snow depletion include periods during which some precipitation occurred, the present studies to determine a coefficient of runoff from melting snow have followed along the lines of that report, in which a precipitation factor was introduced. The equation developed in the 1930 report was

$$R = .5P + C_s (T-27) D, \text{ or } C_s = \frac{R-.5P}{(T-27)D}$$

Where

R = Runoff—*inches*

P = Precipitation during the period—*inches*

T = Average temperature during the period—
degrees fahrenheit

D = Number of days in the period

$(T-27)D$ = Degree days

C_s = Coefficient of runoff of melting snow

It has been suggested that a base temperature of 32° F., instead of 20° F., should be used in deriving an equation for a coefficient of runoff from melting snow, by considering that the diurnal range in temperature approximates a sine curve and integrating the portion of that curve above a horizontal line representing 32° F. The known or observed factors are the maximum and minimum temperatures. In clear weather the diurnal temperature variations do approximate a true sine curve, but during periods of rain and fog this is not true. The air temperatures are measured ordinarily by thermometers in enclosures which exclude the direct rays of the sun. On days when the sun is shining the radiation from the sun causes melting of snow in southern open exposures even when the temperature, as measured by a thermometer in an enclosure, is at or somewhat below 32° F. On cloudy and partly cloudy days this same melting at air temperatures somewhat below freezing may be observed to a lesser degree. As a matter of fact the rapid melting of snow on the ground for any extended period of time is almost always accompanied by some foggy, cloudy weather and more or less precipitation so that a complicated formula, based on the integration of a theoretical sine curve fluctuation of temperature, would seem to offer no advantages over the simple empirical formula with the base temperature of 27° F. used in the studies published in the 1930 report. In further support of the empirical formula, it may be said that a base temperature below 32° is rational, due to the fact that maximum temperatures above 32° frequently accompany averages below the freezing point. During periods of precipitation the clouds cut off the rays of the sun so that for a given temperature the melt due to insulation is decreased. This condition, together with the infiltration, may explain the precipitation factor of 0.5 arrived at in the original statistical analysis.

Precipitation added to snow seeps through it, but if the temperature of the mixture is above freezing, and it has become too heavy to be held by the capillary forces of the snow, it has very little effect on the melting of the snow. The latent heat of fusion of water at 32° F. is 144 British Thermal Units. One inch of rain at say 50° F. would then produce the equivalent of .125 inches of water from snow at 32° F., if all the heat above 32° F. in the rain were used to melt snow. It is apparent, therefore, that the heat from melting snow must come mostly from radiation from the sun and from contact with warm air currents. If a warm air current saturated with moisture comes in

contact with snow it will not only give up heat to melt the snow but in this process some of the moisture in the air will be condensed and in so doing the condensate will give up its latent heat of vaporation.

A graph was included in the September, 1930 report of the Boston Society of Civil Engineers¹ showing the relation between runoff from melting snow and degree days of temperature above 27° F. This graph showed the results of applying the formula to 34 periods on various rivers and reservoirs in New England. The periods with the exception of three instances covered from 5 to 14 days. Since the 1930 report further studies along the same line have been made and thirty-nine new determinations of snow runoff coefficients for various rivers and reservoirs in New England covering periods of from 6 to 24 days have been computed. These determinations together with some maximum day snow runoffs at Somerset and Harriman reservoirs on the Deerfield River, are presented herewith in Tables 12 and 13. They are also shown on the graph on Fig. 32.

TABLE 12
SNOW RUNOFF DATA
CONNECTICUT RIVER AT CONNECTICUT LAKES, NEW HAMPSHIRE
(Drainage Area 83 Square Miles)

Period	No. of Days	Total Runoff Inches	Precipitation For Period Inches	Snow Runoff (Total Less Half of Precipitation)	Degree Days Above 27°	C = Inches Snow Runoff Per Degree Day above 27°
March 10-24, 1936	15	8.30	5.24	5.68	180	.032
April 17-30, 1938	14	7.27	1.55	6.49	271	.024
April 24-30, 1938	7	3.12	.85	2.70	137	.020
April 16-30, 1939	15	3.30	1.22	2.70	130	.021
CONNECTICUT RIVER AT BELLOWS FALLS, VERMONT (Drainage Area 5,400 Square Miles)						
April 1-7, 1940	7	.79	.29	.64	53	.012
CONNECTICUT RIVER AT VERNON, VERMONT (Drainage Area 6,300 Square Miles)						
April 1-7, 1940	7	.93	.32	.77	57	.014
WAITS RIVER AT SOUTH BRANCH, VERMONT (Drainage Area 46 Square Miles)						
April 2-8, 1940	7	1.09	.12	1.03	51	.020
WHITE RIVER AT BETHEL, VERMONT (Drainage Area 241 Square Miles)						
April 1-8, 1940	8	1.14	.12	1.08	67	.016

¹Ibid.: p. 359.

WHITE RIVER AT WEST HARTFORD, VERMONT (Drainage Area 690 Square Miles)						
April 1-8, 1940	8	1.19	.30	1.04	67	.016
SUGAR RIVER AT WEST CLAREMONT, NEW HAMPSHIRE (Drainage Area 269 Square Miles)						
April 1-8, 1940	8	1.28	.26	1.15	67	.017
WEST RIVER AT NEWFANE, VERMONT (Drainage Area 308 Square Miles)						
April 2-8, 1940	7	2.04	.34	1.87	59	.032
MAGALLOWAY RIVER—AZISCOHOS DAM, MAINE (Drainage Area 233 Square Miles)						
April 14-24, 1933	11	3.70	1.0	3.20	146	.022
April 15-22, 1934	8	4.10	1.0	3.60	125	.029
April 18-29, 1935	12	3.21	—	3.21	212	.015
March 10-31, 1936	22	9.50	7.2	5.90	263	.022
PISCATAQUIS RIVER NEAR DOVER-FOXCROFT, MAINE (Drainage Area 286 Square Miles)						
Mar. 13-Apr. 5, 1936	24	15.15	9.17	10.57	326	.032
Apr. 7-23, 1937	17	4.69	1.43	3.97	235	.017
Mar. 24-Apr. 6, 1938	14	2.40	1.34	1.73	76	.023
Apr. 21-30, 1939	10	4.23	1.48	3.49	138	.025
Apr. 11-23, 1940	13	7.75	6.08	4.71	100	.047
LITTLE ANDROSCOGGIN RIVER NEAR SOUTH PARIS, MAINE (Drainage Area 76.2 Square Miles)						
April 6-23, 1937	18	5.48	1.45	4.76	252	.019
March 21-28, 1938	8	2.14	.64	1.82	113	.016
April 17-26, 1939	10	4.72	1.56	3.94	146	.027
April 11-23, 1940	13	4.61	3.64	2.79	113	.025

The average runoff per degree day, as indicated by 20 determinations included in the 1930 report and the present report for Somerset reservoir is .028 inches, and for the 9 determinations included in the two reports for Harriman reservoir it is also .028. The average of 4 determinations at the Connecticut Lakes was .024 and for 4 determinations at Aziscohos dam it was .022. It seems possible that if more determinations had been made for the latter two areas the average might have approached that of the first two. The value C_s as computed in the table includes the base flow of the stream in each case. If an assumed base flow of one cubic foot per second per square mile of drainage area had been deducted from the runoff as used in the formula, the resultant computed average value of C_s would have been reduced a little in excess of .003 inches.

The table shows for the Somerset and Harriman drainage areas, besides the average degree day coefficient, maximum day runoff in

TABLE 13
SNOW RUNOFF DATA
DEERFIELD RIVER AT HARRIMAN, VERMONT
(Drainage Area 154 Square Miles Net)

Period	No. of Days	Total Runoff Inches	Precip. for Period Inches	Snow Runoff (Total Less Half of Precip.)	C _s = Inches		Date (No Precip. on these Dates)	Maximum Day, Snow Runoff		Weather Conditions Previous 48 Hours Average Precip. Inches
					Degree Days Above 27°	Per Degree Day above 27°		Ave. Temp. for Day	Runoff Inches	
Apr. 11-22, 1931	12	7.48	.23	7.37	260	.028	Apr. 12	36°	.89	48° .08
April 1-13, 1932	13	5.66	3.54	3.89	156	.025	Apr. 8	45°	.55	43° .16
April 1-10, 1934	10	4.12	1.04	3.60	164	.022	Apr. 3	45°	.85	44° .91
Mar. 14-25, 1938	12	3.82	1.00	3.32	138	.024	Mar. 24*	50°	.97	49° 0
April 1-7, 1940	7	1.79	.53	1.52	47	.032	Apr. 1	36°	.40	40° 1.53
April 23-30, 1940	8	2.31	.02	2.30	97	.024	Apr. 30	50°	.71	40° 0

*.07 Precip. on March 24.

DEERFIELD RIVER AT SOMERSET, VERMONT
(Drainage Area 30 Square Miles)

Period	No. of Days	Total Runoff Inches	Precip. for Period Inches	Snow Runoff (Total Less Half of Precip.)	Degree Days Above 27°	C _s = Inches		Date (No Precip. on these Dates)	Maximum Day, Snow Runoff		Weather Conditions Previous 48 Hours Average Precip. Inches
						Per Degree Day above 27°	Runoff Inches		Ave. Temp. for Day	Runoff Inches	
April 11-25, 1931	15	7.68	.19	7.59	233	.033		Apr. 23	36°	.79	52° 0
April 8-13, 1932	6	2.29	1.85	1.37	50	.027		Apr. 8	30°	.30	43° .24
Apr. 22-30, 1932	9	3.65	.58	3.36	119	.028		Apr. 23	49°	.67	42° 0
Apr. 16-30, 1933	15	7.68	1.99	6.68	191	.035		Apr. 20	37°	.93	45° 1.47
Apr. 3-11, 1934	9	3.19	.15	3.12	117	.027		Apr. 4	40°	.54	49° .04
Mar. 20-26, 1938	7	3.16	.12	3.10	110	.028		Mar. 25	34°	1.01	54° .04
Apr. 15-30, 1939	16	6.85	2.69	5.50	195	.028		Apr. 29	36°	.82	43° .16
Apr. 1-8, 1940	8	1.61	.47	1.38	37	.037		Apr. 3	30°	.30	34° 0
Apr. 24-30, 1940	7	2.07	0	2.07	74	.028		Apr. 29	34°	.34	36° 0

inches on the drainage area due to snow on days when no appreciable amount of precipitation occurred. The degree day coefficient is not shown for the maximum days because for a single day the snow runoff is greatly influenced by the weather of the previous 48-hour period. For instance, at Somerset reservoir on March 25, 1938, the runoff was 1.01 inches on the 30 square miles of drainage area in spite of the fact that the average temperature for the day was only 2° above freezing, but the average temperature for the previous 48 hours was 22° above freezing. The precipitation during this previous period was only .04 inches. An examination of all the records available in New England indicated this to be also the maximum runoff from snow melt experienced in any one day when there was no apparent contribution from precipitation. At the Connecticut Lakes with a drainage area of 83 square miles a runoff of 1.48 inches on the drainage area was found on March 20, 1936, but there was .01 inches precipitation during that day and .74 inches during the previous two days.

The precipitation and runoff from 154 square miles of drainage area at Harriman reservoir during the second storm at the time of the March, 1936 flood with all readings as of 8:00 a.m. for each day were as follows:

	Inches Runoff	Inches Precipitation
March 15	.35	.01
" 16	.27	.06
" 17	.35	.33
" 18	1.18	1.32
" 19	4.06	2.03
" 20	1.33	.29

This would seem to indicate that on the 19th of March about 2 inches of runoff must have been contributed from melting snow. The runoff into the reservoir was computed from reservoir water surface elevations read to tenths of a foot and a volumetric curve which was made up from a contour survey of the reservoir area. The precipitation is the average of five precipitation stations fairly well distributed over the area. Four of the five precipitation stations reported water content of the snow on the ground ranging from 2 to 2.75 inches on March 25. The fifth station reported no snow on the 25th. It would appear therefore that at 8:00 a.m. on March 19, practically the entire drainage area still had snow cover.

There is a record of runoff during March, 1936, at Lincoln, New

Hampshire, on the Pemigewasset river with a drainage area of 104 square miles where the portion of the runoff from melting snow may have exceeded that at the Harriman reservoir. The records at Lincoln are not as complete as those at Harriman. The only precipitation station on the area is at Lincoln which is at elevation about 800. The area drained contains many peaks at elevations running from 3,000 feet up to 4,700 feet or more. The precipitation and runoff from the 104 square mile area above Lincoln during the second storm at the time of the March, 1936 flood were as follows:

	Inches Runoff	Inches Precipitation
March 15	.29	—
" 16	.31	.20
" 17	.97	.91
" 18	3.90	.19
" 19	4.00	1.23
" 20	1.59	.40

Runoff figures are for calendar days, but precipitation records are taken in the morning. Were the precipitation data representative of the entire drainage area it might indicate a runoff from snow melt of over three inches in twenty-four hours. The Pinkham Notch station, on the east side of mountainous terrain quite similar to a large part of that of the East Branch of the Pemigewasset above Lincoln, reported precipitation in March, 1936, as follows:

March 16	.86 inches
" 17	.44 "
" 18	6.27 "
" 19	4.05 "

This station is also as near to the upper end of the East Branch of the Pemigewasset basin as Lincoln. On account of the great variation in the records of the amount of precipitation in the White Mountains area it would appear that there were not enough stations at which records were taken to make it possible to plot reliable isohyetal lines over the Pemigewasset drainage area above Lincoln. When the difference between the records of precipitation at Lincoln and Pinkham Notch are taken into consideration, it is difficult to draw any definite conclusions as to the amount of runoff from melting snow in any twenty-four hours during the period under consideration.

A paper¹ on the thermodynamics of snow melt, by Mr. W. T.

¹An Outline of the Thermodynamics of Snow Melt, M. T. Wilson—Transactions of the American Geophysical Union, Part I, July, 1941, p. 182.

Wilson of the U. S. Weather Bureau, gives the theory and present knowledge of this subject in considerable detail. In the same publication there is a paper by Mr. Philip Light, also of the U. S. Weather Bureau, on the "Analysis of High Rates of Snow Melting."² In the introduction to this paper Mr. Light states that for high melting rates, the heat contributed by convection and that contributed by the condensation of moisture through turbulent diffusion of warm moist air are the most important heat sources. He defines effective snow melt as combined melt and condensate and develops a theoretical formula for it which is based on wind velocity, air temperatures, vapor pressure and the elevation above sea level. In conclusion he states that "too many approximations are involved in the snow melt from discharge records to claim full verification of the theory on the basis of the limited amount of data analyzed thus far."

The recently formed Eastern Snow Conference is diligently at work on a project, the object of which is to determine the quantity of heat required to melt snow of various qualities. Quality is used in this case similar to the way in which it is used in steam terminology.

Conclusions

As stated in the 1930 report, for smaller drainage areas at higher elevations the degree day runoff relation appears to average higher than .025 inches. For larger drainage areas where there is apt to be a diversity of weather conditions on the area due to its extent, the relation seems to average about .017 inches.

The degree day runoff relation as computed in the table is for average conditions over a considerable period of time and if used to predict approximate runoff over short periods of time should be modified to give consideration to the precipitation and temperature of the preceding days.

The daily maximum flow due to snow melting will frequently be found to be considerably above the daily average in clear weather with temperatures above freezing. The time of the maximum flow varies with the size and shape of the drainage area involved. The maximum average daily runoff from snow melt when accompanied by rain, according to the records examined, is about two inches on the drainage area.

The analysis of runoff in several river basins in the state of

²Ibid., p. 195.

Connecticut during a period in January, 1938, when practically all of the snow was removed and no frost was left in the ground over most of the areas at the end of the period, indicates that the formula here set forth is not applicable to such conditions.

It is understood that the U. S. Weather Bureau is continuing the study of snow melt with special emphasis on the maximum rate and consequent runoff which may be expected under weather conditions most favorable to produce runoff from snow. If a practical, reliable, workable method of predicting snow melt and consequent runoff over moderate sized drainage areas for a period of a day or less, based on data readily obtainable, can be developed, it will be of great help to those who have to do with the handling of flood waters and flood warnings. If in addition a reliable determination of the maximum possible snow melt and consequent runoff for various sections of the country can be determined, much uncertainty in the design of spillway capacity of dams for reservoirs and power plants would be removed. At the present time there is apparently no proven formula for snow melt based on thermodynamics.

FLOOD FREQUENCY

The question of the frequency with which very large floods such as those in New England in 1936 are likely to occur was raised immediately after the flood and many figures were made to determine this on given rivers with varying results, arrived at by different methods. These figures generally gave a frequency of from 300 to 500 years for the 1936 flood.

A complete description of various methods of plotting and computing flood frequencies is given in U. S. Geological Survey Water Supply Paper 771.¹ Some of these methods will be very briefly reviewed in the following discussion of the whole subject of flood frequency, illustrated by examples from the New England rivers.

Practically all flood frequency figures are now plotted on the basis of the following, which plots a given flood at "mid intervals".

$$P = 100 \frac{(m - .5)}{n}$$

Where

P = The percentage of floods which will equal or exceed a given flood

n = The total number of items

m = The serial number of the given flood.

¹U. S. Geological Survey Water Supply Paper 771, "Floods in the United States."

With the points of record thus plotted the general procedure is to use some method of drawing a curve which is extended beyond the length of record. Among the methods are the following: (1) Plotting the points on logarithmic paper and drawing a smooth curve through them and extending this curve by eye. (2) Various statistical methods based on the probability equations as for example, the Hazen and Foster methods which are similar except for certain factors used. (3) The Slade method which uses the statistical method to fix the curve between definite upper and lower limits which are fixed by non-statistically inferred data.

There are great difficulties in applying these methods with any degree of success in fixing the frequency of a very large flood. The length of record of stream flow in this country is not sufficient to obtain satisfactory figures beyond the length of record, if indeed it is satisfactory for even the complete length of record; this will depend on actual record of the stream. For the following discussion the records of flow of the Connecticut River at Thompsonville, based on the readings of the Hartford gauge, have been used. This is a continuous record of the highest annual reading from 1843 to date, thus covering a continuous period of 98 years, including also other earlier records. Some study was also made of the Merrimack River at Lawrence for which a continuous flood record is available for 94 years.

Simple Plotting

Fig. 33C shows the method of extending a curve plotted on logarithmic paper. In this case the floods above 80,000 c.f.p.s. at Hartford during 101 years, 1838 through 1938, were arranged in order of magnitude plotted as described above, that is, $C = \frac{n}{m - .5}$

Where C is the probable frequency of occurrence in years of given value.

This curve shows a frequency for the 1936 flood of once in 265 years. It is possible to draw other curves through the data which would give different results.

This method was used by the Miami Conservancy District endeavoring to determine the frequency of the 1913 Dayton Flood. The data was plotted but it was found that the curve could be satisfactorily extended to show a frequency for that flood of 300, or 3,000 years, so was not used in fixing the size of the flood for design purposes.

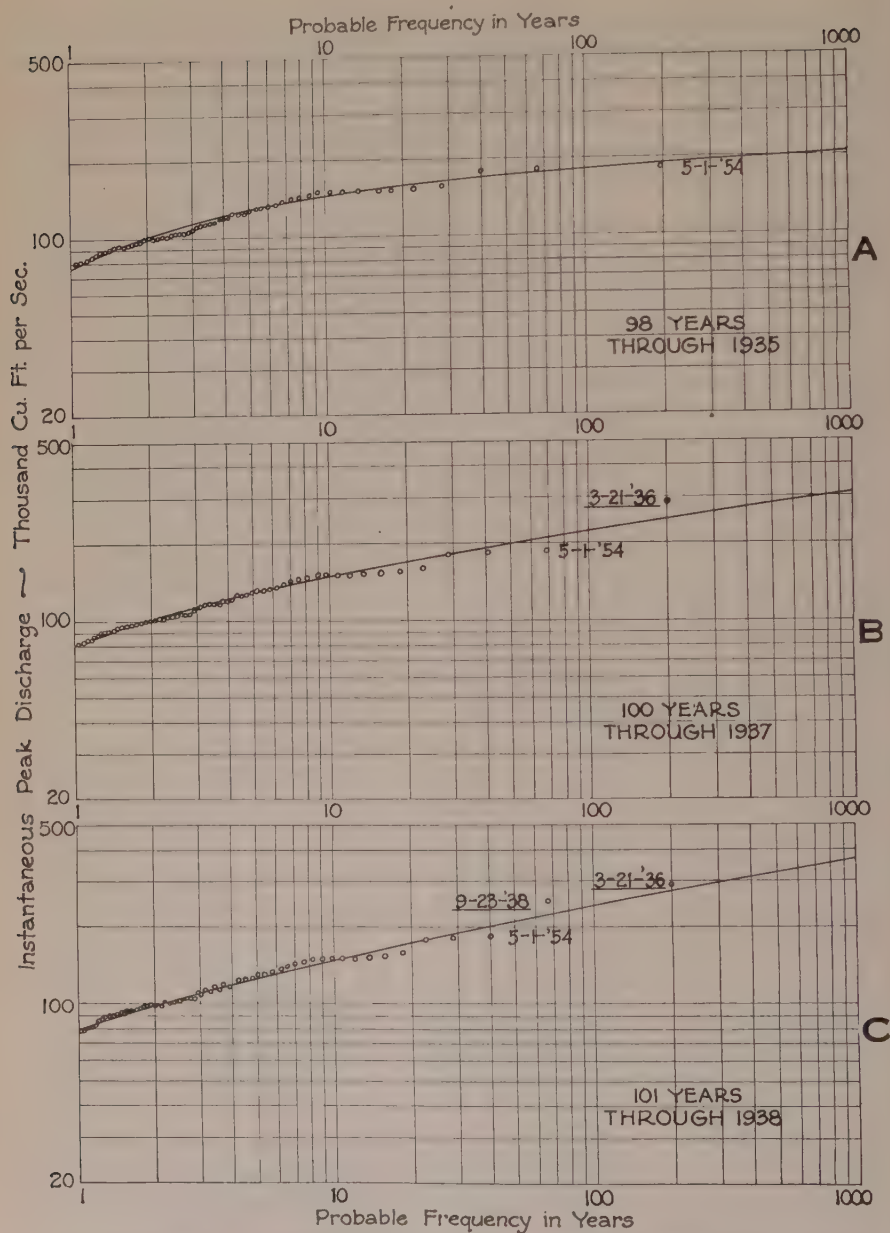


FIG. 33.—PROBABLE FREQUENCY OF PEAK DISCHARGE ON CONNECTICUT RIVER AT HARTFORD, CONN. DRAINAGE AREA, 10,480 SQUARE MILES.

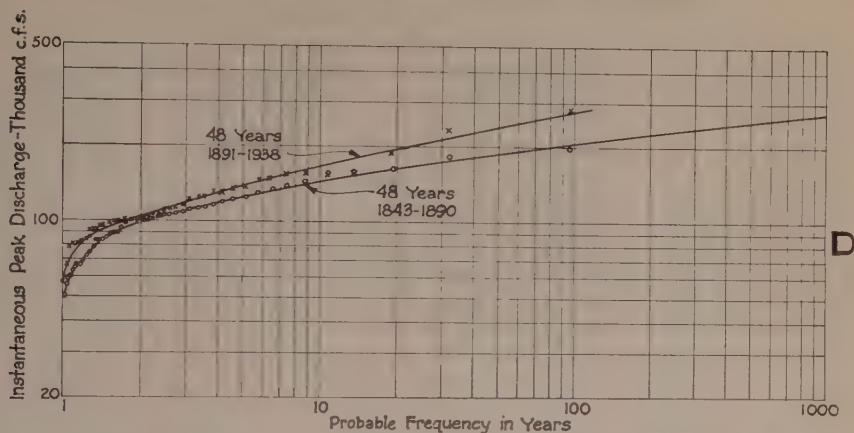


FIG. 33D.—PROBABLE FREQUENCY OF PEAK DISCHARGE ON CONNECTICUT RIVER AT THOMPSONVILLE, CONN.

This is not, however, the only difficulty. Fig. 33A shows the same record of the flood flow of the Connecticut River at Hartford as that of Fig. 33C, except that the records were not carried beyond 1935, three years earlier, thus covering 98 instead of 101 years. This is what would have been found had the flood frequency of the Connecticut River at Hartford been studied in the same way prior to the 1936 flood, instead of in 1939 after the 1938 flood. A smooth curve plotted through this record would show that the 1936 flood probably would never have occurred. This flood record is of a length much greater than most streams of the country, ninety-eight years in all. Fig. 33B shows the plotting of the same record as of 1937, that is, after the 1936 flood but prior to 1938, a total of 100 years.

The records for the 96 years, 1843 to 1938, were divided into two periods of 48 years each and the flood frequency was similarly plotted for each of these periods with the result shown on Fig. 33D, the first period giving a flood equal to that of 1936, a frequency of 1,300 years, and the second period a frequency of 108 years. A 48 year record is longer than exists on some streams; it is clear that it is nowhere nearly long enough to give valid information on the frequency of a large flood.

The "frequency of the 1936 flood" given by these three computations gives the following:

TABLE 14
FREQUENCY OF THE 1936 FLOOD

Fig. 33C,	101 years,	1843 through	1938,	once in 265 years.
Fig. 33A,	97 "	1843 "	1935,	probably never.
Fig. 33B,	100 "	1843 "	1937,	once in 500 years.
Fig. 33D,	48 "	1843 "	1890,	once in 1300 years.
Fig. 33D,	48 "	1890 "	1938,	once in 108 years.

The difficulty comes in handling data of this sort where one flood, 1936 in this case, has a frequency much greater than the length of the given record. In this case, the 1936 flood at Hartford is probably the greatest that has actually occurred in the three hundred years since the Connecticut Valley was settled and if we had a long enough record might show to be even rarer than that. When it occurs in a record of one hundred years it seems incorrect to include it in such a short time and yet if it is entirely neglected we get the impossible results that it would have occurred only once in many thousands of years, if ever.

Any method of figuring, where a 98 year record shows that a given flood would have had a frequency of very many thousands of years or even would never have occurred, and a record of three years later, 101 years, shows a frequency of once in two hundred and sixty-five years, hardly seems worth the effort involved in the computation.

Hazen's and Foster's Probability Methods

The flows of the Connecticut River at Thompsonville have been analyzed by skew probability curves described by Allen Hazen¹ and later by H. Alden Foster.² A flood frequency curve, Foster Type III, was figured first on the basis of ninety-three years' record through 1935, shown on Fig. 34A, then on the 94 year record through 1936 shown on Fig. 34B and from the 96 year record through 1938 shown on Fig. 34C. The frequency of the 1936 flood is determined from these, as shown on Table 15, to be 16,700 years from the 93 year record of 1843 through 1935, and 333 years from the 96 year record of 1843 through 1938.

A frequency curve was also figured for the same record through 1936 but adjusted by assuming that the 1936 flood occurred once in 300 years. This is shown on Fig. 35A.

To show the difference that can be found by using two separate continuous records the 96 years were divided into two 48 year halves. The results are shown on Table 15 and Fig. 35B. The frequencies of the 1936 flood thus determined for the same river but for two different 48 year periods being 8000 and 150. Practically the same discrepancies but somewhat different frequencies are found if Hazen's factors are used instead of Foster's.

¹Flood Flows, Allen Hazen. John Wiley Sons, 1930.

²Theoretical Frequency Curves, H. A. Foster, Transactions American Society of Civil Engineers, vol. 87, pp. 142-173, 1924.

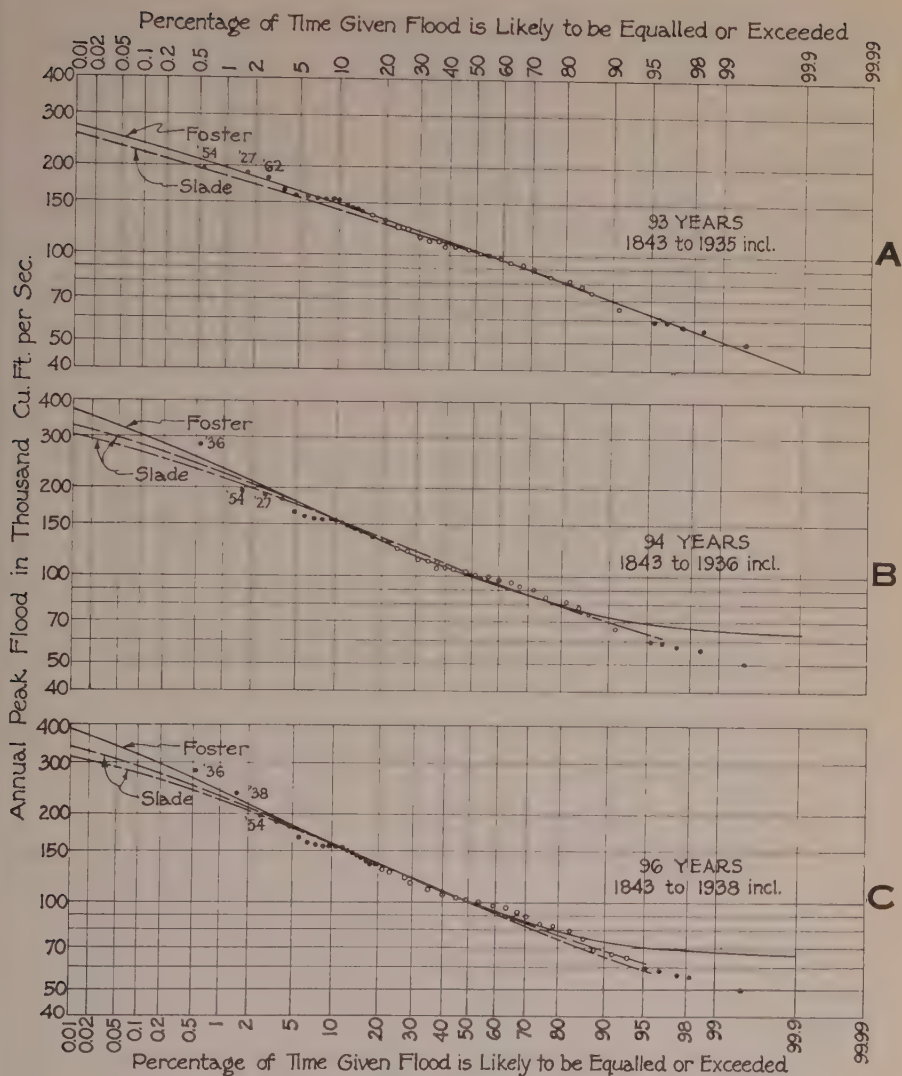


FIG. 34.—FREQUENCY OF ANNUAL FLOODS ON CONNECTICUT RIVER AT THOMPSONVILLE, CONN.

Slade's Method

The frequency of floods from these records also has been computed using Slade's method³ of a completely bounded function which

³"An Asymmetric Probability Function," J. J. Slade, Transactions American Society of Civil Engineers, Vol. 101, p. 35, 1936.

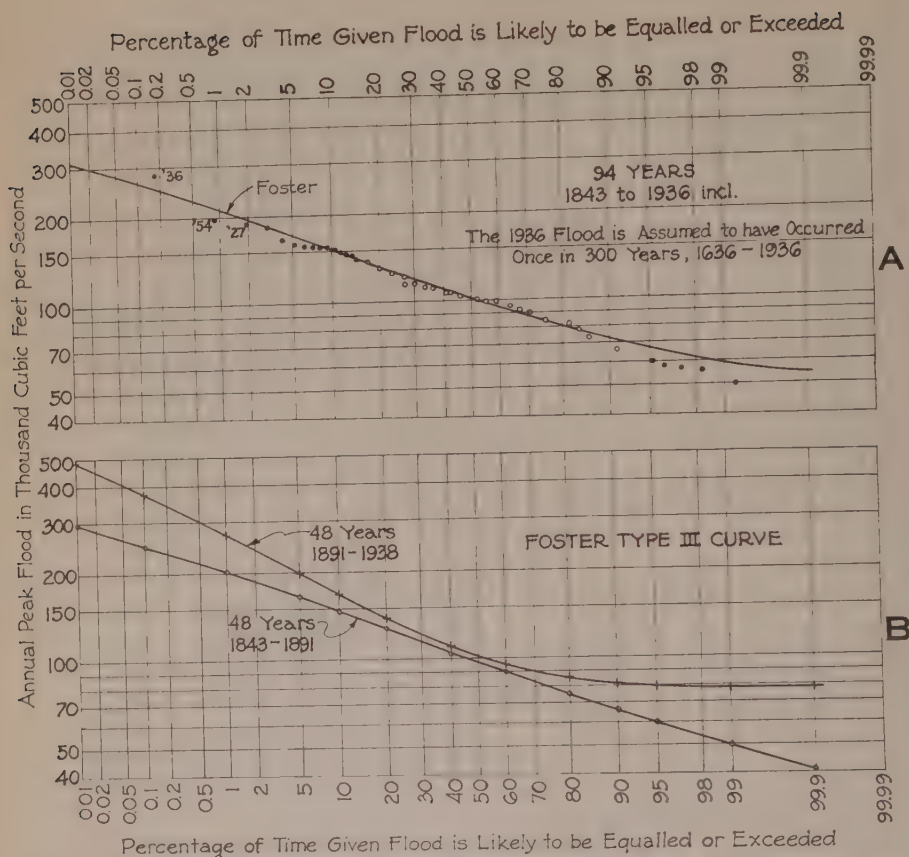


FIG. 35.—FREQUENCY OF ANNUAL FLOODS ON CONNECTICUT RIVER AT THOMPSONVILLE, CONN. DRAINAGE AREA 9,637 SQUARE MILES. FLOWS ARE BASED ON HARTFORD GAGE.

fixes the upper and lower limits of the probability curve by other than statistical data. The limits fixed make some difference in the result. It was hoped that this method which fixed the maximum would simplify the difficulty of having a very rare flood occur in a comparatively short record. The results obtained are shown on Table 16 and are plotted on the curves on Fig. 34. The same thing appears as was noted in the other methods of figuring. The frequency of the 1936 year flood is found to be 10,000 years for the 93 year record 1843 to 1935, and 1540 to 670 years for the 96 year record 1843 to 1938, depending on the maximum and minimum limits chosen.

Similar figures using Foster's and Slade's methods were made up

TABLE 15
FREQUENCY OF 1936 FLOOD AT THOMPSONVILLE, CONNECTICUT
FOR VARIOUS PERIODS OF RECORD BY FOSTER TYPE III CURVES

Figure No.	Length of Record Years	Dates	Frequency in Years 1936 Period
3A	93	1843 to 1935	16,700
3B	94	1843 to 1936	450
3C	96	1843 through 1938	333
3D	94	1843 to 1936 (1936 assumed once in 300 years)	2,500
3E	48	1843 through 1890	8,000
3E	48	1890 through 1938	150

TABLE 16
FREQUENCY OF 1936 FLOOD ON THE CONNECTICUT RIVER AT THOMPSONVILLE,
CONN., BY SLADE'S TOTALLY BOUNDED FUNCTION

Fig. No.	Years of Record	Date	Maximum Assumed C.F.S.	Minimum	Frequency in Years of 1936 Flood
4A	93	1843 to 1935	530,000	25,000	10,000
4B	94	1843 to 1936	"	"	2,200
4B	94	" "	"	40,000	1,110
4C	96	" "	"	25,000	1,540
4C	96	" "	"	40,000	670

TABLE 17
MERRIMACK RIVER AT LAWRENCE
FREQUENCY OF 1936 FLOOD FOR VARIOUS PERIODS OF RECORD
BY FOSTER'S TYPE III CURVES

	Length of Record	Dates	Frequency of 1936 Flood	Maximum Assumed Minimum	Minimum
	90	1846 to 1935	21,000		
	91	1846 to 1936	400		
BY SLADE'S METHOD					
	90	1846 to 1935	10,000	350,000	15,000
			26,000	350,000	10,000
			47,500	250,000	15,000
	91	1846 to 1936	1,050	410,000	15,000
			1,430	350,000	15,000
			2,000	350,000	10,000
			3,000	250,000	15,000

for the Merrimack River at Lawrence. The results, shown on Table 17, show the same discrepancy as those for the Connecticut River.

Thus a student of the flood frequencies of, for example, the Connecticut River at Hartford, working with a ninety-three year record, a very long record as they go in this country, would have found that a flood of 282,000 c.f.s. (the 1936 flood peak) would have occurred once in many thousand years if it was not beyond all probability of ever occurring, depending on the method used. The next year after the 1936 flood he has to revise his figures. He does so including the 1936 flood and finds that this was not such a very rare flood after all, in fact might be expected in from 250 to 500 years, depending on the method he uses. He might have some doubts about his figures on account of the way the 1936 flood plots so far out of line with the previous 100 years. Two years later, however, he has to refigure his results again on account of another large flood, the second highest in the 100 year record. This shows even shorter frequencies for the 282,000 c.f.s. flood. The result is that in the short period of three years he has three very different curves of frequency varying from several thousand to somewhere around two hundred years for a flood the size of that in 1936. The conclusion is that while these methods may be mathematically correct, none of them are suitable to apply with all data obtained from flood records, except possibly in the case of a fairly long record of floods which does not include any very great variation, that is, that does not include a very rare flood, such for example as the Tennessee River record analyzed in U. S. Geological Survey Water Supply Paper 771. They may be used for drawing a curve through the actual points plotted from such a record, but there is grave doubt as to whether any extension beyond the length of the record by any method gives a result at all reliable. If the record contains one very rare flood such as the 1936 flood on the Connecticut and Merrimack Rivers the question arises of how that particular flood should be treated. If it is included in the record in which it manifestly does not fit, that is, the 1936 flood in the 100 year record on the Connecticut River, the result probably will give too low frequencies, and if it is omitted, the resulting curve will show frequencies probably too high for the actual history.

It seems to this Committee that the ordinary river has a normal flood regime, reaching normal maximum of a flood which may be expected perhaps once or twice a century, and that then due to very exceptional conditions there may come a very large flood that has a frequency of several hundred to a thousand or more years. While the

frequency figures of the flood regime of a river with a 100 year record may be assembled and plotted for the ordinary floods, up to say that flood expected to be equaled or exceeded once or twice in a century, the attempt to put a frequency beyond that on these very rare floods gives such varying results that it is hardly worth the attempt.

The use of flood frequency figures also appears to be limited in scope. There seems to be no reason whatever why the frequency should be used in determining the size of flood for which the spillway of a dam should be designed. The capacity of a dam spillway is much better determined by many other factors, such as the type of construction, the damage likely to result in failure, and importance of the structure rather than whether the flood which will exceed its capacity is likely to come once in one or ten thousand years.

The use of frequency figures comes down chiefly to the single question of economics on flood control projects, as, for example, how much money it is advisable to spend compared to the corresponding benefits. Here again their use is also limited to the lower frequency values, for the damage inflicted but once in a thousand years only contributes a little to the yearly figure of damage because it is spread out over so long a period. This being the case, the simplest method of figuring would appear to be the best. Simple plotting with a curve fitted to the points as near as possible without any attempt to extend it much beyond the record would seem to be sufficiently accurate for almost any flood frequency computation.

The committee makes no attempt to fix closely the frequency of the 1936 and 1938 floods in New England. Actually, on the Connecticut the former is believed to be the largest in the 300 years since the valley was settled. The frequencies generally assigned to this vary from about 250 to 500 years, and about the same on the Merrimack. The committee is satisfied to say that the 1936 flood on the larger rivers in New England was undoubtedly a major flood with a "frequency" of several hundred up to perhaps a thousand years.

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CHAPTER VI

Flood Losses and Economics

FLOOD *losses* are ordinarily recorded for the purpose of determining the need for, or the extent of, remedial measures required. *Benefits* of such measures are based on the reduction or prevention of losses, together with any additional increases in the value and utility of property that result from flood protection.

The losses caused *by each individual flood* may be divided into three basic classes:

- (1) Direct—physical damage.
- (2) Indirect—service, business, etc.
- (3) Intangible—not subject to direct monetary evaluation—including life, health, social and economic security.

TABLE 18—DIRECT FLOOD LOSSES—SCHEDULE

RESIDENTIAL	Residences, not including farm houses Grounds and cleanup Personal property, furnishings, etc.
COMMERCIAL	Buildings Equipment Stock Cleanup
INDUSTRIAL (Manufacturing)	Buildings Structures Grounds Equipment Stock, raw material, finished goods Cleanup
UTILITY	Properties of Power and Gas Telephone and Telegraph Water Works
RURAL	Land, erosion and deposition Buildings and improvements Equipment and property Stored crop and food Livestock Timber Crop

HIGHWAY	Bridges
	Pavements
	Grading
	Highway transport and operating equipment, goods in transport
RAILROAD	Track, road-bed and culverts
	Bridges
	Buildings and yards
	Goods, stored or in transit
PUBLIC	Rolling stock and equipment
	Damage to all property owned by Federal, State, and Municipal Governments, or public agencies
	River structures
	Emergency labor

DIRECT FLOOD LOSSES

Direct flood losses are the physical damage to property and goods, measured by the present-day cost of repair, or the replacement in kind, and the cost of cleanup and moving goods. In Table 18 is given a schedule of Direct Flood losses by types, with the more important subdivisions. Damages are obtained by appraisal and summation of industrial, utility, railroad, highway, public, and other important individual losses and estimates from typical samples or characteristic areas of residential, commercial and agricultural losses.

TABLE 19—INDIRECT FLOOD LOSSES—SCHEDULE

INDUSTRIAL AND COMMERCIAL	Wages
	Overhead, salaries, fixed charges
COMMERCIAL	Liquidated damages on non-filled contracts
	Starting and stopping operations
	Normal business
	Good will
RESIDENTIAL	Extra operating costs
	Disruption of business
	Evacuation and emergency quarters
	Loss of rent
RURAL	Flood relief costs
	Public health, etc.
	Similar to residential, and also
	Delayed crop plantings
HIGHWAY	Reduction in crop yield
	Sale of farm products
	Service interruption
	Traffic interruption
	Cost of detours

RAILROAD	Service interruption Traffic interruption Increased cost of operation
UTILITY	Interruption and loss of revenue for the following facilities Power and Gas Telephone and Telegraph Water Works Navigation
PUBLIC	Interruption of service and facilities

INDIRECT FLOOD LOSSES

Indirect losses are the value or cost of the service or use lost or made necessary by flood conditions not chargeable to direct loss. They include losses of business and wages, costs of relief, re-routing of communications and transport, and similar losses both within and without the flood area, during the period of flood and subsequent rehabilitation. A schedule of indirect losses is given in Table 19. Indirect losses are tangible monetary losses that are sustained over wide areas by a great variety of individuals and agencies. They may be evaluated by summation of individual losses supplemented by rational analyses and sampling methods. They are more conveniently estimated as a proportion of the direct losses, varying from 0.1 to 1.0 or more, based upon analyses of various types of properties in representative areas.

TABLE 20—INTANGIBLE FLOOD LOSSES—PARTIAL SCHEDULE
(Not directly determinable but reflected in real losses of property value)

LOSS OF LIFE	
MENTAL DISTRESS	Suicides Worry over past losses Apprehension of future conditions
PHYSICAL DISTRESS	Sickness Physical hardship Discomfort and inconvenience
LOWER USE OF PROPERTY	Lower type of business, lower class of tenant, lower rental Abandonment of basements, etc. Exodus of industries and inhabitants Exodus of capital, loans curtailed, credit suspended Tendency towards slum area
INTERRUPTION OF NORMAL GROWTH	Stopping of industrial expansion or growth Stopping of residential development
GENERAL LOSSES OUTSIDE FLOOD AREA	Losses to remote parties through contact with parties in flood area, which were not evaluated under indirect loss. Inconvenience to travelers, etc.

INTANGIBLE LOSSES

Floods cause many losses of an intangible nature, which are not susceptible of direct evaluation, although they are sometimes of importance. In Table 20 is a schedule of the more important losses typical of this class.

DIRECT AND INDIRECT LOSSES IN RECENT FLOODS

Table 21 summarizes flood loss data for the rivers of New England in the three recent large floods of 1927, 1936 and 1938.

On the larger river systems, direct and indirect losses in dollars totaled as follows:

Year of Flood	MERRIMACK			CONNECTICUT		
	Direct	Indirect	Total	Direct	Indirect	Total
1927	2,365,000	1,635,000	4,000,000	15,526,000	14,044,000	29,570,000
1936	19,600,000	15,400,000	35,000,000	34,500,000	31,780,000	66,280,000
1938	3,560,000	2,350,000	6,000,000	25,600,000	22,890,000	48,490,000

Merrimack Basin. The 1927 flood was confined principally to headwater areas and to dams and other structures in or near the normal channel of the main stream. The 1936 flood was outstanding. Eight lives were lost and flood damage and temporary evacuation of residents was general throughout the entire basin. In 1938, four lives were lost and the effects of the flood were particularly severe in the Contoocook and Piscataquog sections of the basin. Columns 13 and 14 give the maximum loss per square mile of drainage area (in 1936) as \$3,900 direct, and \$7,000 total of direct and indirect.

Connecticut Basin. The loss of life was as follows: 1927—21 lives, 1936—11 lives, and 1938—8 lives. These three great floods caused direct and indirect losses totaling nearly \$150,000,000 in 11 years, and affected areas never before flooded.

These floods may be characterized as follows:

1927—An upper river flood, especially upon the Vermont and New Hampshire tributaries.

1936—A main river flood, with tributary flows in general not excessive.

1938—A lower river flood, chiefly on the Massachusetts and Connecticut tributaries.

TABLE 21 (Continued)

River or Area	Drainage Area Square Miles	DIRECT AND INDIRECT FLOOD LOSSES (Million Dollars)						PER SQ. MILE (dollars)		MAXIMUM LOSS Total Direct and Indirect
		1927			1936			1938		
		Direct	Indirect	Total	Direct	Indirect	Total	Direct	Indirect	Total
MASSACHUSETTS										
Millers	393	—	—	2.60	3.73			1938	9,500	(b) 17,700
Deerfield (c)	465	—	—	.44	4.11			1938	8,800	(b) 16,500
Chicopee	724	—	—	1.42	4.78			1938	6,600	(b) 12,200
Westfield	520	.99	—	.38	1.34			1938	2,600	(b) 4,800
CONNECTICUT										
Farmington	613	.04	—	.34	1.25			1938	2,050	(b) 3,800
Conn. River and small streams	4.37	—	—	28.29	7.89			1936		
CONNECTICUT R.—										
TOTAL	11,320	15.53	14.04	29.57	66.28	31.78	22.89	48.49	3,120	6,000
WINOOSKI—VT.	1,080	11.0	2.5	13.5	.16	.28	.12	40	1927	10,200
THAMES—MASS.										
AND CONN.	1,473	.07	—	3.47	3.75	7.22	5.87	11.49	1938	4,950
HOUSATONIC	1,948	—	—	1.10	.95	2.05	2.31	2.05	1938	1,200
(a) Based upon 1.70×direct losses.										
(b) Based upon 1.87×direct losses.										
(c) Below Harriman Reservoir.										
(d) Losses on French River based on 1936 flood.										

(c) Below Hariman Reservoir.

(d) Losses on French River based on 1936 flood.

The maximum losses per square mile of drainage area for the whole river which resulted from the 1936 flood are \$3,120 direct, and \$6,000 total. The three major floods in the Connecticut Valley—viz., 1927, 1936, 1938—have centered on different portions of the basin, and the composite figures for the Connecticut River, using the maximum losses in each individual tributary watershed, are: direct, \$4,800 per square mile, and total, \$9,200 per square mile.

River	Year	Direct and Indirect Losses per Square Mile	
		Direct	Total
White River, Vermont	1927	\$5,900	\$11,000
Passumpsic River, Vermont	1927	5,100	9,500
Millers River, Mass.	1938	9,500	17,700
Deerfield River, Mass.	1938	8,800	16,500
Chicopee River, Mass.	1938	6,600	12,200

It is evident that the highest losses per square mile occurred in 1938, particularly on the Millers, Deerfield, and Chicopee Rivers, and losses approaching the same unit amounts on Vermont streams in 1927. Upwards of \$10,000 per square mile of direct losses and \$18,000 total, was reached on the Millers River in 1938.

It is of interest to note that direct plus indirect losses per square mile on the Miami River in Ohio in 1913 were apparently nearly \$20,000, a total of \$100,000,000¹ for 5,433 square miles at Dayton. This is in contrast to \$7,000 on the Merrimack River and \$5,900 on the Connecticut River, indicating the greater unit damages on the Miami River in 1913.

RECURRING LOSSES

Recurring flood losses are those which may be expected from similar future floods. They are estimated from *experienced* losses by eliminating losses which are clearly non-recurring by reason of altered usage or abandonment, or the nature of replacement or repair. For example, a bridge replacement should, if practicable, be at such an elevation above flood level that it would not again be subject to being swept away or damaged by another flood. Similarly, highway repairs or replacements may often be made in such a manner as to make future flood damage non-recurrent or largely so.

Recurring losses usually have a marked tendency to become less

¹The figures compiled in 1914 (The Miami Valley and the 1913 Flood, Miami Conservancy District, Technical Reports, Part 1, page 117) give a total of \$66,800,000, not including damage to farms and to some public utilities. It is not clear whether these figures include any indirect damages. The above figure of \$100,000,000 is an approximation believed to be less than the total direct and indirect damages.

with each successive great flood; as properties and activities become adjusted to greater flood experience, new capital is no longer introduced, and property frequently falls to a lower level of value and utility. On the contrary in individual areas, recurring losses may often exceed experienced losses where idle mills have been reoccupied or new development is taking place. Recurring losses provide the basis for estimating losses prevented by proposed flood protection, equivalent to direct and indirect benefits.

DEPRECIATION AS A MEASURE OF FLOOD LOSSES

This alternative method for the determination of losses is to determine the depreciation of value as a result of flooding. This is taken as the difference in value of the property before and after flooding, by determining the sale value of property in the flood areas as accurately as possible. Annual loss may be computed from the normal interest or earnings (say 5%) on the total depreciation, using some factor for the diminishing value of depreciation in the years after the flood. Such depreciation should be taken not in addition to the direct, indirect and intangible damage but as an alternate method for determining the same total.

There is a difference of opinion among the members of the Committee as to the desirability of including depreciation as a factor in the determination of flood losses and benefits. Some consider that since depreciation in property values follows a flood, it must basically be a result of the sum of the direct and indirect losses, and that the determination of depreciation by the lessening in value of property due to flood is merely another, less perfect, method of estimating the total direct and indirect flood losses. The difficulty in using this method of arriving at flood losses appears to be in accurately determining property depreciation from the floods alone, as natural depreciation from advancing age and obsolescence, as well as other economic causes, are often difficult to exclude or segregate. There is also usually exaggeration in the estimates of property owners at times of large floods, which, however, becomes less as time goes on. This may be allowed for but is difficult to evaluate. Others feel that as some of the indirect and intangible losses are difficult to evaluate and may be overlooked, the use of the depreciation of property values may furnish a more complete basis for such evaluation than the sum of the direct and indirect losses or benefits alone. Hence, the depreciation method may

be used as an alternate method, or to supplement the direct and indirect loss method, for the determination of intangible losses and benefits in certain highly developed areas.

The consideration of a portion of depreciation in property values when they exceed the direct and indirect losses, as a means of including allowance for unincluded losses, may be desirable in some cases.

AVERAGE ANNUAL FLOOD LOSSES

Two methods of determination of average annual direct losses are in use:

(1) Where a long record of floods and corresponding losses is available the total loss may be determined and the result divided by the period of record in years.

(2) Average annual direct loss is determined as the average ordinate of a direct loss-frequency curve or table, determined by combination of the following relationships:

- (a) The river or watershed, if large, may be divided into suitable reaches and a stage- or discharge-loss relation prepared for each reach based on summation of individual direct losses or use of the recurring preventable direct losses of floods of record as a control.
- (b) The relation of discharge to frequency is determined from discharge records by accepted methods.

Annual indirect losses may be estimated from their relation to the corresponding direct loss, or indirect losses may be determined by similar methods.

AVERAGE ANNUAL BENEFITS OF FLOOD PROTECTION

Benefits are classified as follows:

(1) *Direct*—prevention of direct recurring losses, or physical damage prevented.

(2) *Indirect*—indirect losses of use or service which are prevented.

(3) *Intangible benefits*—other benefits, indeterminable in character, including prevention of loss of life and promotion of the general welfare and social security of the population.

(4) *Increases of property value*, if any, not taken care of in (1), (2) and (3).

Direct and indirect benefits are computed as the reduction in recurring losses. Natural average annual direct and indirect losses are computed as above. Modified losses are computed by similar methods from the frequency of loss as modified by protective works.

Average annual flood protection benefits for proposed plans of protection works have been determined by the U. S. Engineer Offices for the Merrimack River as follows:

Direct	\$622,000
Indirect	521,000
Total	\$1,143,000

Capitalized at 5 per cent, this will warrant an expenditure of about \$23,000,000. The amount now planned to be expended is approximately \$22,000,000. This is the equivalent of about \$4,400 per square mile of drainage area or 63% of the maximum direct and indirect losses per square mile experienced in the 1936 flood.

For the Connecticut River as follows:

Direct	\$1,170,800*
Indirect	1,029,100*
Total	\$2,199,900*

This total, capitalized at 5 per cent, is about \$43,000,000. The amount now planned to be expended for flood control works is about \$72,000,000. This amounts to about \$6,300 per square mile of drainage area or about 105% of the total of direct and indirect losses per square mile experienced in the 1936 flood.

The annual benefits for the Connecticut River as prepared by the U. S. Engineer Office includes the item:

Increases of property value
(Exclusive of direct and indirect) = \$1,940,200.

The increases in property value were credited principally to the highly developed lower valley areas near Hartford and Springfield. If this item is included it results in total yearly benefits of \$4,140,000, which capitalized at 5 per cent is about \$83,000,000. This practically doubles the flood benefits and the opinion of the Committee is divided as to

*Based on Reservoir and Levee Plan of House Documents 724 and 653, 76th Congress, 3rd Session.

the advisability of including such a large allowance in addition to direct and indirect benefits.

FLOOD DAMAGE TO PUBLIC WATER SUPPLIES

The damage to public water supplies in 1936 was general in New England and due primarily to flood conditions. The heavy precipitation and floods which accompanied the hurricane of 1938 resulted in considerable damage to public water supplies in Central Massachusetts and parts of New Hampshire and Connecticut, but none at all in Maine and a small amount in Vermont and was confined in two municipalities in Rhode Island. The greater portion of the damage in 1938 resulted from the hurricane. The estimated damage to public water supplies in New England during the 1936 flood amounted to approximately \$1,500,000 as compared to less than one-third of that amount for the flood in 1938.

1936 Flood

In Maine ice jams caused the flooding of the pumping station and filtration plant at Richmond. Floods caused the inundation of wells and pumping stations at Brewer on two separate occasions and the failure of pipe lines when bridges upon which they were located failed. The submarine crossing at Bingham also failed. The pumping station at Biddeford was isolated by extreme flood and at Rumford a large 16" main across the Androscoggin River was washed out. At Auburn and Oldtown 8" mains were washed out and at South Paris an impounding dam was destroyed. At Waterville an 8" and two 12" mains laid on bridges failed with the bridges and an 8" submerged pipe was washed away. In the town of Pittsfield the pumping station was inundated. Perhaps the most unusual condition existing in the state of Maine was that at Brewer where the weight of the ice was reported to have been the cause of the collapse of the two submarine pipes.

In New Hampshire few public water supplies were seriously affected. However, the flood resulted in broken water mains in Conway, Pembroke, Concord and Peterboro and the flooding of well fields at Hudson, Greenfield, Plymouth, Concord, Rochester and Derry and the flooding of pumping stations at Hudson, Greenfield and Nashua. A dam was destroyed at Goffstown and the filtration plant at Franklin was flooded. The flooding of the well fields and pumping stations caused only temporary difficulties requiring the hauling of water for domestic consumption and chlorination of several of the supplies as a preliminary measure.

In Vermont the authorities report that there was no appreciable damage to public water supplies during the 1936 flood.

In Massachusetts water mains were washed out by floods in 32 communities, the greatest damage of this kind having occurred in Chicopee, Fitchburg, Hadley, Holyoke, Lowell and West Springfield. Damage to sources of supply were suffered in 22 municipalities, by far the greatest damage of this kind resulting from the flooding of the works of the cities of Lowell and Lawrence. The disaster at Lawrence resulted in the construction of a new filtration plant at an elevation above maximum flood height.

In the 1936 flood minor damages were experienced on some of the smaller rivers but the greater portion of the damage occurred in the Valleys of the Nashua, Merrimack and Connecticut Rivers in Massachusetts.

In Rhode Island the authorities report that the flood of 1936 did not damage Rhode Island supplies.

In Connecticut the dug well at Grosvenordale was flooded and the top section of the dam at Willimantic gave way but the supply was maintained. The large municipalities along the Connecticut River in Massachusetts and Connecticut are supplied from upland reservoirs and the sources of supplies were uninterrupted during the flood of 1936. Such catastrophes as occurred were due to breakage of water mains and the inability to operate control gates.

Health authorities in all of the New England States report the flooding of a large number of private wells. Prompt action by health and water works officials prevented the supplying of unsafe water from public works and warning by state and local health departments by means of the radio resulted in the exercise of extreme care in the use of private sources of supply. The significant conclusion was reached that there was no increase in communicable diseases which could be attributed to the flood.

1938 Flood

There was no damage to public water supplies in the state of Maine during the period of the 1938 flood and hurricane.

In the state of New Hampshire the damage was less serious than that in 1936. Several water supply failures were due to lack of power caused by the destruction of transmission lines by the hurricane. In a few cases pumping station equipment was damaged, but many municipalities had profited from the experience of the 1936 flood. One

institution's supply was blocked by mud deposited during the flood and another institution's supply was completely destroyed. More or less serious interruptions were occasioned by the breaking of water mains at Keene, Henniker, Peterborough, Warner and North Woodstock. It is reported that the damage to water supplies and sewerage works in New Hampshire during the 1938 flood amounted to approximately \$90,000, but no major systems were affected.

In Vermont it is reported that the Castleton water supply was destroyed but other towns suffered minor damage such as washout of sections of pipe. In general the damage due to flood was not great in 1938.

In Massachusetts the greatest damage occurred in the central and western portions of the state and resulted for the most part from the breakage of water mains. However, the water supply works at Ware, Hardwick, East Brookfield, Monson State Hospital and North Brookfield were seriously affected by the flood waters. The washout of the dam in North Brookfield caused the flooding of a pond in East Brookfield and the washout of the dam and water mains in the latter community. The washing out of the main pipe line supplying East Brookfield resulted in the emptying of the standpipe which was overturned in the hurricane.

There was no damage due to upland flood waters in Rhode Island although tidal waves at Newport washed out a dam causing a water supply pond to be drained and at Jamestown flooded the filtration plant.

In Connecticut broken mains were experienced in East Hartford and North Canaan and at East Hartford the dam on upper Salmon Brook Reservoir was washed out. The dam was washed out in South Glastonbury and a portion of the dam gave away at Willimantic. At two of the state institutions wells were flooded.

As in the case of the 1936 flood emergency measures were necessary to insure the safety of public and private water supplies and although many private wells were flooded the state health departments report no increase in communicable diseases due to the flood and hurricane.

SUMMARY AND CONCLUSION

In general the floods on the smaller rivers in 1936 were less damaging than on the larger rivers although many pumping stations

and tubular fields were temporarily flooded. The major damage to public water supplies occurred in the Merrimac River Valley in Massachusetts where the flood inundated the supply works located near the river. The flood in the Connecticut River, while inundating large areas, failed to affect the upland systems of supply of the large metropolitan areas in Central Massachusetts and Connecticut. The attention of the engineer is immediately directed to the failure of bridges which resulted in the breakage of pipe lines and to the necessity of properly anchoring and protecting submarine crossings.

The similarity of experience in the 1938 flood to that of the 1936 flood with broken mains and the flooding of pumping stations and well fields must again impress upon the engineer the importance of considering the effect of loss of pipe lines due to possible bridge failures, of protecting submarine pipes and of the necessity of locating pumping stations above flood level or adequately protecting them from inundation. The experience during the flood of 1936 and the flood and hurricane of 1938 further emphasized the need of auxiliary pumping equipment for use in time of failure of electrical transmission lines.

The freedom from increase in communicable disease following both of these major disasters speaks well for the prompt activity of the public health officials in the various states, in the installation of chlorinating equipment for use in connection with flooded or emergency sources of public water supply and in the education of the public against the use of private water supplies of unknown quality.

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CHAPTER VII

Flood Control Programs and Works

Prior to the 1936 flood there was little done in the way of flood control in New England, the only project of any magnitude being the construction of three flood control reservoirs in the Winooski River Basin. Since the 1936 and 1938 floods, however, a very large amount of work for flood control and flood protection on New England rivers has been completed, or is nearing completion. This has been done by the Federal Government, the States, and in some cases the cities and towns along the rivers, either with or without Federal contributions. This work is briefly described in this chapter.

FEDERAL WORK

Merrimack River Basin

The U. S. Engineer office in Boston has been in charge of the work on the Merrimack River and other local work in the Merrimack drainage area.

The only completed flood control works are the local flood protection projects undertaken after the March, 1936, flood with Emergency Relief Appropriation funds. This consisted of: (1) channel improvements in the Merrimack River at Lowell, Mass., from Pawtucket Dam to the lower limits of the city, completed in June, 1938, at a cost of about \$800,000; (2) channel, rectification and realignment, wall construction, placement of riprap, removal of dams, bridges and retaining walls, and construction of a reinforced concrete conduit, all along a 5-mile reach of the North Branch of the Nashua River in the city of Fitchburg, completed in January, 1938, at a cost of approximately \$1,370,000; and (3) construction of a 2,250-foot reinforced concrete flood wall and a 2,000-foot reinforced concrete pressure conduit in the city of Haverhill, completed in March, 1938, at a cost of about \$1,750,000.

The comprehensive plan for flood control in the Merrimack River Basin was authorized by the Flood Control Act approved June 22, 1936, and amended by the Flood Control Act approved June 28, 1938. This authorized project provided for the construction of a system of

flood control reservoirs and related flood control works which may be found justified by the Chief of Engineers at a total estimated cost of \$21,000,000. The specific items of work selected by the Chief of Engineers under this project consist of five reservoirs, namely Franklin Falls, Blackwater, Hopkinton-Everett, West Peterboro and Mountain Brook, and local flood protection works at Nashua, N. H., Lowell, Mass., and North Andover, Mass.

The location of the works proposed is shown on Fig. 36. General data on the reservoir projects, including estimated costs, are summarized in Table 22.

TABLE 22.—FLOOD-CONTROL RESERVOIRS PROPOSED FOR THE MERRIMACK RIVER SYSTEM

Reservoir	River	Drainage area sq. mi.	Capacity inches of run-off	Storage acre feet	Total costs
Franklin Falls	Merrimack	1,000	3.2	170,000	\$7,883,000
Blackwater	Blackwater	128	6.8	46,000	1,300,000
Hopkinton-Everett	Contoocook	432	6.5	150,000	11,270,000
West Peterboro	Contoocook	44	6.8	16,000	1,011,000
Mountain Brook	Contoocook	14	6.4	4,800	344,000

Of the projects selected for the comprehensive plan, work has been started only on Franklin Falls and Blackwater Reservoirs. The Blackwater Reservoir was scheduled to be completed in 1941 and Franklin Falls by June 30, 1942. Definite project plans have been approved for the Hopkinton-Everett, West Peterboro and Mountain Brook Reservoirs, but funds for the initiation of construction on these projects are not available at this time. No specific data are available for the local protection works proposed for Nashua, Lowell and North Andover. Definite project reports for this work are in the course of preparation.

The flood control project on the North Branch of the Nashua River in Fitchburg, Mass., was built after the 1936 flood and finished before the 1938 flood. The flood of March 1936 had a magnitude of about 11,500 c.f.s. through the city. This was the largest flood of record and caused damages estimated at \$2,760,000. Extensive channel improvements over a five-mile reach of the river within the city were undertaken in August, 1936, and completed in January, 1938. Funds for the work were provided by allotments, totalling \$1,374,000, from the Emergency Relief Appropriation Acts of 1936 and 1937. The work consisted of channel excavation and realignment totalling about 460,000 cubic yards, the construction of about 25,000 cubic

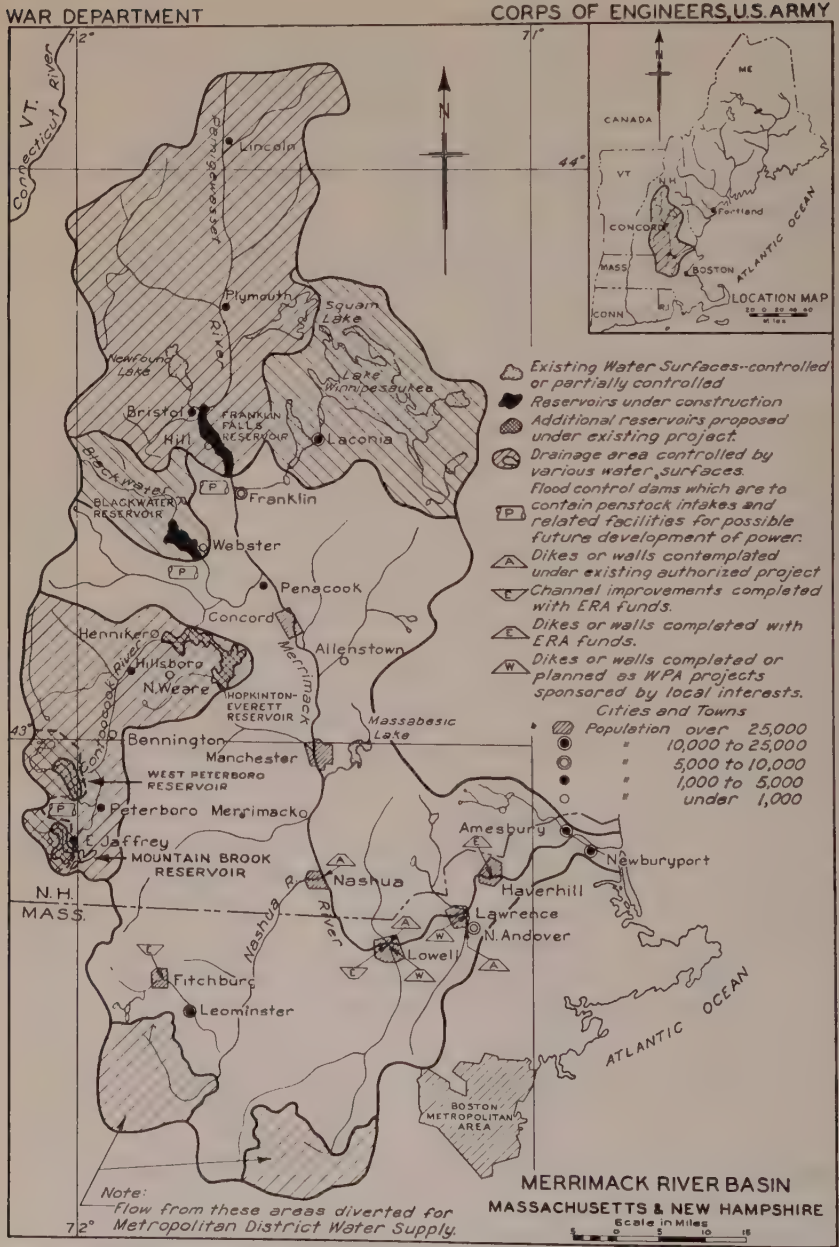


FIG. 36.—PROPOSED FLOOD CONTROL WORKS, MERRIMACK RIVER BASIN.

yards of stone and concrete walls, the placement of about 65,000 square yards of riprap, the reconstruction of a railroad trestle and a bridge pier, the removal of several existing dams, bridges and retaining walls, and the construction of 1,120 feet of reinforced concrete conduit for the diversion of the tributary Punch Brook. The September 1938 flood had a maximum peak flow of 8,500 c.f.s. at Fitchburg. This flood was confined within the banks of the improved channel and no flood damages occurred in the city. It is estimated that the channel improvements prevented over \$1,500,000 flood damages in the 1938 flood.

Connecticut River Basin

The flood control work on the Connecticut River has been in charge of the U. S. Engineer Office in Providence, R. I. The Flood Control Act of 1938 revised the previous plan covered by the 1936 Flood Control Act. The later plan called for the construction of twenty reservoirs and seven levee and flood walls projects at a total cost of \$47,000,000, to which local interests were expected to contribute \$1,264,000 for land and damages, pumping plants and drainage works. Annual charges were estimated at \$2,729,000 and annual benefits at \$5,268,000. This comprehensive plan was reviewed in the light of the flood of September, 1938, and the list of reservoirs revised as shown in Table 23. These reservoirs control 26% of the drainage area of the river above Hartford; Fig. 37, shows their location. Table 24 shows the authorized flood protection work along the Connecticut River.

The flood control work now under way includes the construction of three dams—at Knightville, Mass., Birch Hill, Mass., and Surrey Mountain, N. H.—and of local protection works at seven localities along the lower Connecticut River—Hartford and East Hartford, Conn., and Springfield, West Springfield, Chicopee, Holyoke and Northampton, Mass. All three of the dams will be completed in 1941. Local protection work at the various cities is in some instances complete. At Northampton the work is complete. At Holyoke protection of the upper half of the city is complete. At Springfield the work is complete; at West Springfield three pumping stations have yet to be finished. The protection works at Hartford will be complete in 1942; two pumping stations, a section of levee and wall along the river front, and the Park River Conduit are yet to be built. Construction has been initiated on the latter two items. At East Hartford work

TABLE 23.—FLOOD-CONTROL RESERVOIRS PROPOSED FOR THE CONNECTICUT RIVER SYSTEM†

Reservoir	River	State	Drainage area sq. mi.	Flood control capacity Inches of run-off	Acre— feet	Total costs
Knightville	Westfield	Mass.	164	4.5	39,300	\$2,751,000
West Brookfield	Chicopee (Quaboag)	Mass.	106	6.0	33,900	2,317,000
Barre Falls	Chicopee (Ware)	Mass.	57	8.0	24,300	965,000
Tully	Millers (Tully)	Mass.	50	8.3	22,150	759,000
Birch Hill	Millers	Mass.	175	5.3	49,900	3,005,000
Honey Hill	Ashuelot (South Br.)	N. H.	70	7.0	26,200	1,935,000
Surry Mountain	Ashuelot	N. H.	100	6.1	32,500	1,620,000
Claremont	Sugar	N. H.	245	6.0	78,400	5,160,000
West Canaan	Mascoma	N. H.	80	8.0	34,100	2,520,000
Sugar Hill	Ammonoosuc	N. H.	246	7.0	91,600	6,530,000
Williamsville	West	Vt.	400	7.0	150,000	6,280,000
Cambridgeport	Saxtons	Vt.	58	7.0	21,600	1,975,000
Brockway	Williams	Vt.	101	6.0	32,300	2,944,000
North Springfield	Black	Vt.	102*	6.2	33,400	2,018,000
Ludlow	Black	Vt.	56	8.0	23,900	2,200,000
North Hartland	Ottawaquechee	Vt.	222	6.0	71,100	3,630,000
South Tunbridge	White (First Branch)	Vt.	102	6.0	32,600	2,275,000
Gaysville	White	Vt.	226	7.0	84,300	4,785,000
Union Village	Ompompanoosuc	Vt.	126	4.5	20,200	2,376,000
Victory	Passumpsic	Vt.	66	8.0	28,200	1,415,000
TOTALS			2,752		939,950	\$57,460,000

†Engineering News Record, July 17, 1941, Page 50, from H. D. 724, 76th Congress, 3rd Session.

*Exclusive of drainage area above Ludlow.

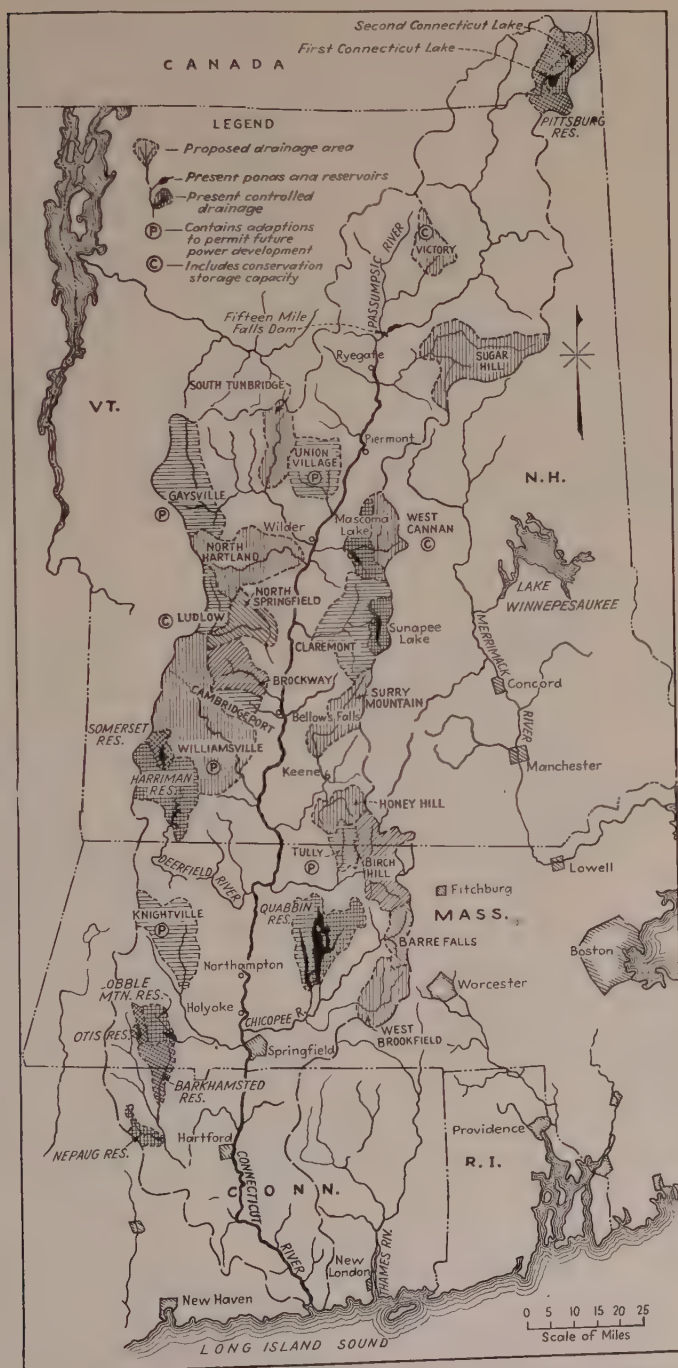


FIG. 37.—CONNECTICUT RIVER—PROPOSED FLOOD CONTROL RESERVOIRS.
ENGINEERING NEWS RECORD, JULY 17, 1941.

TABLE 24.—EXISTING AND AUTHORIZED LEVEES, FLOOD WALLS, AND APPURTENANT WORKS ALONG THE CONNECTICUT RIVER

Location	Character of work	Length of levee	Cost
Hatfield	Levees	State 8,600* Town 3,000 U.S.E.D. 1,240	\$ 60,500* 13,000 41,800
Hadley	Levees	State 6,688* U.S.E.D. 2,900	26,200* 42,100
Northampton	Levees, diversion canal, pumping stat. and other work	Private 2,000 U.S.E.D. 7,330	7,500 1,248,000
South Hadley Falls	Concrete wall	State 1,700*	28,000*
Holyoke	Levee, concrete wall, pumping stat. and other work	State 140 U.S.E.D. 17,230	1,200 2,713,000
Springdale (Holyoke)	Levee, pumping plant and other work	City 10,175	224,400
Chicopee	Levees, walls, and pumping stations	City 8,000 U.S.E.D. 25,745	30,000 2,188,000
Springfield	Levees, concrete walls, and other work	City 6,200 U.S.E.D. 28,475	335,000 1,287,200
West Springfield	Levees, concrete walls, and other work	Private 11,500 U.S.E.D. 28,225	45,000 1,837,900
Agawam	Levee	State 450	1,000
Hartford	Levees, walls, pumping sta- tion and other work	Private 9,500 City 15,500 U.S.E.D. 75,200	125,000 1,301,000 6,390,500
East Hartford	Levees, walls, and pumping stations	U.S.E.D. 21,350	2,407,000
TOTAL			\$20,353,300

*Also listed under work done by Massachusetts.

on the completion of the dike is well along, and construction of two of the three necessary pumping stations has been started.

Designs for two additional dams—Union Village, Vt., and Tully, Mass.—have been completed. Construction of these two projects awaits appropriation of funds.

STATE AND LOCAL WORK

In addition to the flood control work done and under way by the Federal Government there has been extensive work done by the various New England states, which is outlined briefly below. In all the states many bridges have been rebuilt since the three large floods of 1927, 1936 and 1938. Practically all of these have been built with larger waterways and often enlarged channel approaches. These are not generally listed among the flood control projects although they are great flood improvements. The list given below may not be complete and does not cover any private or local work done by cities and towns.

Maine

After the 1936 flood highway work was done on Route 2 in Milford, Greenbush, and Passadumkeag. Five projects, totalling 12.9 miles have been built. Ordinary improvements were made but in addition the elevation of the roadway was raised so as to be above high water elevation which can be expected in very rare instances. Three new bridges were built to provide equalization of water elevation on each side of the new highway, a condition which was formerly obtained by water going across the road. The approximate cost of these five projects including the bridges, is \$372,000.

New Hampshire

Two reservoirs, primarily for conservation, which were constructed by the Water Resources Board at Pittsburg on the Connecticut River and at North Weare on the Contoocook River, were justified somewhat by their flood control values. Following the 1927 flood and to a larger extent following the 1938 flood, the Highway Department has done considerable dredging of stream beds in order to provide a better stream condition and more capacity where necessary to protect main highways and bridges.

Vermont

After the 1927 flood, three flood control reservoirs were built as

Federal Works projects in the Winooski River Basin. Since this no other work except in connection with rebuilding washed-out bridges and highways has been done.

Massachusetts

After the 1927 flood a special act was passed authorizing the Department of Public Works to dredge the accumulated materials from the Hoosic River in the towns of North Adams and Clarksburg and a considerable expenditure was made in repairing the highways and bridges which were damaged. This work was purely rehabilitation.

After the 1936 flood, work was done by the Waterways Division of the Department of Public Works on the Connecticut River dikes in cooperation with the Federal Government.

After the 1938 flood a special session of the Legislature passed the following acts:

Chapter 505, provided funds for highway work made necessary by the recent hurricane and floods. Under item (a) for the construction, reconstruction and repair of town and county ways, \$8,750,000 was provided, and under item (b), for the maintenance, reconstruction and repair of State highways, \$4,500,000. This money was definitely provided for rehabilitation, although the many hundreds of bridges restored were built with greater waterways and improved foundations so that, judging from the 1936 expenditures, it is probable that few if any of these bridges will be damaged again under similar conditions. The roadways were also protected by riprap and concrete walls, additional waterway was provided in the streams adjacent to such highway improvement, and frequently points of land were cut off and other stream improvements made from the point of view of protecting the highway against future damage.

Under Chapter 506, the Department of Public Works was authorized to make certain improvements in rivers and streams made necessary by the flood and this act was interpreted as being for repairing damages and removing obstructions. This act carried an appropriation of \$1,000,000, the expenditure of which is shown in Table 25. There were a great many projects carried out over a widely scattered area and it is very difficult to separate the money which was expended for repairs and that which was expended to prevent future damage.

Chapter 507 provided funds for the repairs, reconstruction and replacement of State property and under that act approximately

\$160,000 was given to the Department for repairs and approximately \$70,000 of this was spent on rebuilding and repairing the dikes along the Connecticut River which had been damaged by the high water.

Chapter 513, the Acts of 1939, gave for the first time to the Department of Public Works permanent control of the structures within streams to prevent unreasonable encroachments. Since the passage of that act all bridges or culverts which have been constructed are passed on by the engineers of the Waterways Division with consideration as to their capacity to pass floods. This act also carried \$1,000,000, approximately \$900,000 of which was used for stream clearance and flood prevention work. While a large part of this has gone for actually clearing obstructions from the streams, a reasonable proportion of it has been spent with the idea of increasing the capacity of the streams so that flow which causes "zero damage" may be increased. No funds have been spent for reservoir construction.

Table 25 gives a list of the work done and its cost under the various legislative acts after the flood of 1938:

TABLE 25.

Connecticut River			
Repairs to dikes and stream clearance work in Hatfield, Hadley, West Springfield, Chicopee and Montague			\$90,879
Hoosic River			
<i>Adams:</i> Channel improvement	\$ 43,046		
Wall and riprap	8,335		
Tophet Brook improvement	110,288		
<i>No. Adams:</i> Stream clearance	94,351		
Bridge repairs and riprap	9,937		
<i>Clarksburg:</i> Channel excavation and riprap	5,174		
<i>Williamstown:</i> Channel and excavation	732		\$271,863
Housatonic River			
<i>Pittsfield:</i> Stream clearance	2,498		
Channel excavation, walls and riprap	51,733		
<i>Great Barrington:</i> Channel improvement	6,195		
<i>Lee:</i> Dike and riprap	1,933		62,359
Millers River			
<i>Athol:</i> Channel excavation, retaining walls, bridge, crest gates, and riprap	553,339		
<i>Orange:</i> Channel excavation, railroad bridge, walls, riprap, crest gates in "New Home" Dam	235,306		
<i>Erving:</i> Channel excavation, dikes and riprap	14,854		

TABLE 25.—(continued)

<i>South Royalston</i> : Channel excavation	6,619	
<i>Templeton</i> : Channel excavation	9,570	
<i>Wendell</i> : Channel excavation and bridge improvement	14,093	
<i>Winchendon</i> : Channel excavation, river walls and riprap	121,158	954,939
Mumford River		
<i>Sutton</i> : Stream clearance	9,440	9,440
Quinebaug River		
<i>Southbridge</i> : Channel excavation and dike	25,503	
<i>Dudley</i> : Wasteway at East Dudley	24,978	50,481
Ware River		
<i>Barre</i> : Stream clearance, tree removal, repairs to dam	36,344	
<i>East Brookfield</i> : Repairs at Lake Lashaway	14,461	
<i>No. Brookfield</i> : Dam reconstruction	10,850	
<i>Hardwick</i> : Channel improvement	5,274	
<i>Thorndike</i> : Channel excavation and riprap	11,256	
<i>Warren</i> : Dike construction	10,410	88,595
Westfield River		
<i>Russell</i> : Dam abutment and riprap	53,812	
<i>Huntington</i> : Channel improvement and riprap	96,269	
<i>Chester</i> : River wall, excavation and riprap	8,308	158,389
TOTAL		1,686,945
Under a state-wide W.P.A. project covering all rivers		
537 miles of river covered for tree removal, minor		
excavations and riprap protection		900,985
TOTAL		\$2,587,930
On the above projects State costs =	\$2,013,371	
Federal costs =	574,559	

Connecticut

The State of Connecticut has authorized a channel clearance project at Putnam on the Quinebaug River which included dredging and some building of dikes, the total cost of which will be in the vicinity of \$40,000, including the Federal contribution by the W.P.A. The town of Plainfield has a W.P.A. project under way for putting the Moosup River into a conduit as a flood control measure, at an estimated cost of somewhat in excess of \$90,000.

Rhode Island

Various minor local work.

The 1930 Report reached the following conclusions:

"To provide fully against the ultimate flood is an impossibility. The flood problem is the common one of economics met with in many other engineering projects. It is economic impossibility at the present time to prevent highway accidents by the complete elimination of all grade crossings and the construction of single-way roads. Nor can the forces of nature be economically controlled to the extent that inconvenience will not be suffered as a result of heavy storms. Generally speaking, a storage capacity of 3 to 4 inches on the drainage area will eliminate practically all damage due to 3 or 4 inches of flood runoff, and will reduce the damage from 6 and 8 inch floods to moderate proportions. A storage capacity of 4 inches on the drainage area represents approximately 10 million cubic feet per square mile. Its cost in New England will usually be between \$600 and \$1,000 per million cubic feet, making the cost of such flood prevention between \$6,000 and \$10,000 per square mile. This is far beyond the amount that is in most cases warranted for flood prevention alone, even taking into account the frequency of destructive floods.

"The above costs would apply to the construction of storage reservoirs solely for the purpose of flood prevention. By combining the use of storage for power and flood prevention it may be possible in some cases to obtain the necessary storage to keep the great floods within bounds, at a substantially lower cost.

"Reservoirs even if built solely for power use afford a large measure of flood protection, if operated as they should be with good judgment. Moreover, storage above spillway level, together with intelligent gate operation, will alone greatly cut down flood peaks. This flood remedy is becoming more and more available as storage development progresses, and warrants the encouragement in every way possible of comprehensive power and storage development of our river systems.

"The Committee does not find that any extensive system of general flood control is warranted, though flood control works may be advisable locally in special cases. The most hopeful general measure toward diminishing flood damage here in New England is to stimulate to the greatest extent possible the development of power storage reservoirs. Vermont has already started this movement, and by the

cooperation of Federal and State authorities and public service corporations is developing comprehensive plans for such reservoirs on its rivers.

"Legislation to aid in the formation of storage regulating districts, with provision for proper allocation of cost in accordance with results secured, whether for power or flood protection, appears to be the next logical step.

"If the other New England States will cooperate in this movement, it will pave the way for not only the economic development of our river systems, but also achieve the possible reduction of flood hazard to a point where this will be unimportant. This general program will require a long time to complete, but should be investigated, properly planned, and carried out, step by step, in the future as one of the essential measures toward the prosperity of New England."

Since that report was written there have been two more disastrous floods and after each of them there was an insistent and extensive public demand for some protection. The plan of storage regulating districts which the 1930 Committee favored was more or less followed in the State compact plans which were originally worked out for the flood control projects proposed after the 1936 flood. This left the control of the reservoirs in the hands of the states and it is believed would have led to use of the reservoirs for wider purposes. With the refusal of the Federal Government to accede to this plan, the greater part of the flood control work has been done and paid for by the Federal Government.

As to whether the actual savings which may be experienced are sufficient to justify the large cost of the program, there is a divided opinion among the Committee. There is no division of opinion about the improvement attained whether the cost can be justified or not. The work was begun at a time when large expenditures on public works programs were undertaken for employment purposes. The benefit from this work is certainly as great as or greater than, that from many other projects of the public works programs.

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CHAPTER VIII

Flood Warnings and Flood Emergency Provisions

GENERAL

The subject of flood warnings was treated briefly in the report of the earlier flood committee of the society. Since that report was published, the public, through disastrous experience, has become more flood conscious and a great deal has been accomplished in the manner in which data for flood warnings are secured and disseminated. The present status of this situation will be set forth here in some detail.

Timely and comprehensive forecasts of probable flood conditions have a real economic value to both urban and rural interests in New England. The fact that disastrous floods may occur more than once in a generation, or even more frequently, is ample reason why the determination of flood dangers should be the subject of constant study, and the results of such studies broadcast in the most effective way.

Urban life in New England has developed around the seaports and water power sites on the rivers and streams. Obviously we are not here concerned with damage to developments at seaports. Urban centers on streams, however, have suffered severe damage and economic loss during past years due to flood waters. Lack of intelligent town planning, and defective zone ordinances during the development period, have resulted in much industrial and domestic development within the area subject to flood waters.

In some places walls and levees have been built to protect industrial and commercial areas where the developments have encroached on the river flood plains. Extensions to existing protective works and new protective works are being built or are planned for larger places on some of our rivers. Reservoirs have also been built and more are planned to reduce the flood peaks. In many places, however, about all that can be done now to reduce the preventable damages and keep loss of life to a minimum is the dissemination of adequate flood warnings.

Rural life in New England has, to a considerable extent, developed along the fertile intervale lands bordering the rivers and tributaries. The high water, which may frequently overflow these lands,

contributes much to the fertility and building up of the soil, and to that extent is beneficial. The normal flood or freshet does no great harm to these areas. The major floods, however, may constitute a real danger to property and people in many rural areas. The inhabitants of these areas are much interested in the time major floods may be expected, and their probable magnitude. To this extent flood warnings will be of value to the rural dweller.

On the larger streams there are numerous agencies which are interested in river operation and regulation, and through these, systems of river forecasts and flood warnings have been developed. There are, however, many drainage areas in New England where this type of service is practically non-existent.

Urban needs are met to some extent if someone is warned in each center. Committees, both large and small, must have a sense of public responsibility aroused to give such warnings real weight. One of the greatest needs in flood warnings is probably in this field. The general effectiveness of some of the present flood warning systems from the standpoint of the individual property holder is to be questioned, due largely to the lack of detail and the number of people effectively reached.

STATE OF MAINE ORGANIZATIONS

Although Maine is the largest state in New England, it has no weather bureau office engaged in river and flood work within its boundaries. As a result, while the Weather Bureau can and does predict storm and temperature conditions which may cause heavy snow melt in the State of Maine, it would be almost impossible for it to function as a flood warning organization over most of the State.

Fortunately there are competent, experienced, and well trained engineering organizations, employed by the power and industrial companies on the three great rivers in Maine, which have available over their telephone lines daily, and when necessary, hourly readings of precipitation and river stages at many points on the watersheds in which they are interested. Snow surveys in the western part of the State are made monthly after January 1st of each year, and more often if conditions of snowfall indicate the need; regular stations for each twenty-five square miles of area are located so as to cover all ranges of altitude. In times of danger the engineers on each river keep in touch with the Weather Bureau forecasts, together with precipitation, temperature, and river stage conditions at many points

and issue warnings whenever it seems advisable. These warnings are given to the local newspaper, and are usually included in the local radio news broadcasts two or three times a day, or oftener if it seems desirable. There seems to be a feeling in the State that the matter of flood warnings has been handled very well.

It is surprising to learn of the number of individuals in commercial establishments and industrial plants to whom water stage in terms of feet elevation on a gage mean very little. There has been in the past a general feeling by many that they have never encountered flood damages and probably never will. Much loss has occurred to organizations who have operated on such an assumption. A real service can be rendered to this class. General flood warnings, however, sent out year after year with little if any loss to the individual rapidly lose what value they may merit.

U. S. WEATHER BUREAU FLOOD FORECASTING SERVICE

The U. S. Weather Bureau is charged with the responsibility of gathering hydrologic data, and the formulation and dissemination of river forecasts and flood warnings. In this work the Connecticut River Basin is covered by the Hartford, Connecticut, office, and the Merrimack River Basin is covered by the Concord, New Hampshire, office. These offices, through the medium of the Weather Bureau Teletype network, are in a position to appraise at frequent intervals the progress and development of meteorological conditions. This is of particular value when abnormal conditions of precipitation and stream flow are imminent.

In addition to a study of conditions aloft, the river work is organized to watch closely the changes in precipitation, river stage, and stream flow at strategic points in the basins under observation. Daily readings of precipitation and stream flow are obtained from several stations by telephone and telegraph, while less important stations report daily by post card. In addition, through the cooperation of the Connecticut Valley Power Exchange, and the New England Power Company on the Connecticut, and the Public Service Company of New Hampshire on the Merrimack, stream flow and precipitation data can be obtained at frequent intervals from a number of points along the main streams and tributaries. Also, through the cooperation of the U. S. Geological Survey, the New England Telephone & Telegraph Company, and the Southern New England Telephone Company, re-

ports of stream flow are received by telephone from the most important tributary streams when needed. Stations reporting precipitation only are of two types—those which report daily, and those which report only on occasion as per instructions. Table 26 gives a list of the regularly reporting stations.

TABLE 26.—STATIONS REPORTING STREAM FLOW AND PRECIPITATION IN THE CONNECTICUT AND MERRIMACK VALLEYS

CONNECTICUT VALLEY		MERRIMACK VALLEY	
<i>Stream Flow and Precipitation—Daily</i>			
<i>Connecticut River</i>		<i>Passumpsic River</i>	<i>Pemigewasset River</i>
1 North Stratford, N. H.		2 Passumpsic, Vt.	1 Plymouth, N. H.
2 McIndoes Falls, Vt.			2 Bristol, N. H.
1 South Newbury, Vt.	<i>White River</i>		
2 Wilder, Vt.			<i>Merrimack River</i>
3 White River Junction, Vt.	1 West Hartford, Vt.		
2 Bellows Falls, Vt.			2 Garvins Falls, N. H.
1 Walpole, N. H.	<i>West River</i>		2 Manchester, N. H.
2 Vernon, Vt.			2 Lowell, Mass.
2 Turners Falls, Mass.	2 Newfane, Vt.		2 Lawrence, Mass.
3 Montague City, Mass.			
1 Holyoke, Mass.			
1 Springfield, Mass.			
<i>Precipitation—Daily</i>			
First Connecticut Lake, N. H.		Lincoln, N. H.	
West Stewartstown, N. H.		Lakeport, N. H.	
Bethlehem, N. H.		Concord, Mass.	
St. Johnsbury, Vt.			
Rochester, Vt.			
<i>Precipitation—Occasionally as per Instructions</i>			
Chelsea, Vt.		Cannon Mt., N. H.	
Newport, N. H.		Glenclyff, N. H.	
Somerset, Vt.		Waterville, N. H.	
Keene, N. H.		Alexandria, N. H.	
Ware, Mass.		Grafton, N. H.	
		Bradford, N. H.	

1. Reports received by post card.
2. Reports received from cooperating power companies.
3. Reports received by wire.

Connecticut River

The procedure followed by the Hartford Weather Bureau Office for reporting amounts of heavy precipitation and the issuance of fore-

casts in the Connecticut basin is briefly as follows: For convenience in handling the report, the day is divided into four six-hour periods starting at 1:30 A.M. When 1.00 inch or more of precipitation falls in a 24 hour period up to the end of one of these time intervals, the first telegram is dispatched to the office giving the amount, time of beginning and ending, and any other pertinent information such as times of heaviest rain, change in snow cover, etc. A report is then sent in at the end of each six-hour period as long as the precipitation continues. If the rain has been reported as stopped in one message but begins again in the next or second successive six-hour period, another report is sent in if the amount of rain equals or exceeds 0.50 inch. If a 24-hour period goes by with no precipitation, or an amount too small to report, the process begins over again. All of the river and rainfall stations, the daily reporting rainfall stations, and the occasional rainfall stations are instructed to send in reports according to this plan.

All of the stations keep a record showing the daily river stage, when recorded, the 24-hour precipitation, the time of beginning and ending of precipitation, the amount of snow if the precipitation fell as snow, the amount of snow on the ground, and other miscellaneous data. This information is kept on file in the river district center, and is also published in climatological and hydrologic bulletins issued by the Weather Bureau.

The river forecasts made for the Connecticut River are mostly those pertaining to flood warnings but occasionally there are requests for forecasts of stages at lower levels, especially when construction work is under way. Because of the rush of work at the Weather Bureau river centers at times of high water and the necessity for getting out a forecast as soon as possible, the river forecasting plan must be devised so that reasonably accurate results can be obtained in the most efficient manner. To that end it has been found best to compromise and use a stage-discharge method, as well as a gage-height relation method, for determining maximum stages. It is recognized that the gage-height relation method is the easiest and least time consuming method but in the past it has been confined in its use to large streams. It can be applied to smaller streams also, whenever the time of run-off from one station to another is sufficient so that proper warnings can be given.

On the Connecticut River it has been found that the gage-height relations from White River Junction, Vermont, downstream can be

relied on quite satisfactorily under many conditions. But naturally on a stream of this size with numerous tributaries, this method should not be used alone. To supplement and check it, a method has been developed whereby the hydrograph has been built up in four reaches of the river; above South Newbury, Vermont; White River Junction, Vermont; Montague City, Massachusetts; and Hartford. The unit hydrograph method is used to determine the inflow from each contributing tributary in the reach. When the maximum flow is calculated for the uppermost reach, the hydrograph is routed downstream. The Weather Bureau office is aided in this part of the work by the U. S. Geological Survey Offices at Boston, Massachusetts and Hartford, Connecticut, in that they supply rating curves and stream flow information to keep the Weather Bureau stream rating data up to date.

In regard to the dissemination of forecasts and warnings, in past years it was very difficult to get word to all who had property endangered along the river. All the Weather Bureau could do was to send out the warnings by telegraph or telephone to a number of persons, most of whom were river observers, urging that the information be given as much publicity as possible. The development of communication facilities during the last few years and the splendid cooperation of the New England and Southern New England Telephone Companies has made it possible to organize a much more effective system for the distribution of warnings. The set-up now includes the following:

1. Telegrams and telephone calls to all river observers advising them of expected stages.
2. Radio broadcasts direct from the Weather Bureau office in which stages and forecasts are given in detail. Bulletins to four radio stations in Hartford as new information comes in and conditions change.
3. Direct telephone calls to officials in the principal communities in the valley. Among those notified directly are the Holyoke Water Power Company, the Planning Board of the City of Springfield, and the Committee appointed by the Mayor in Hartford. These, in turn, set into action the local organizations in their respective communities.

Merrimack River

The Merrimack River District, centered at the Weather Bureau office in Concord is organized along very similar lines to the plan in

effect at Hartford. Stream flow and precipitation are reported daily from some stations, and precipitation only is reported occasionally from other stations when certain rates of rainfall are reached. Notifications are by telegraph, direct telephone calls, radio broadcasts, and through the newspapers. Work in the Merrimack Basin is not carried out in as great detail as in the Connecticut because of the smaller size of the basin.

The lower Merrimack valley was settled very early and has a number of large industrial centers developed on the original flood plain of the river. The largest community in the basin is Lowell where the Proprietors of the Locks and Canals on Merrimack River have been in charge of the water power for more than a hundred years. With a century's record of river operation, and floods experienced, this organization is excellently equipped to be of great assistance in times of stress. The present set-up with reference to flood warnings and flood emergencies is simple and informal, but so far has met the situation well. In cooperation with others, information which permits the ready determination of stream flow is received daily by telephone or post card from several upstream points. When required, additional information is obtained at more frequent intervals by telephone. These reports cover the daily record of the important drainage areas of the main river and principal tributaries which determine the flow of the river at Concord and Manchester in New Hampshire, and Lowell, Lawrence, and Haverhill in Massachusetts, where the population and property are greatest. All these records are tabulated and compared with previous records in order to know from day to day whether dangerous conditions are ahead or if no special precautions will be necessary. Thus daily and hourly records from half a dozen stations have made the problem of anticipating maximum and moderate flows a comparatively simple one, and made it possible to issue flood warnings calculated either to warn the public in advance or to quiet its fears.

SNOW SURVEYS

During the last few seasons a program of snow surveying has been carried on in the upper Merrimack Basin. Beginning about January 1st, and continuing through the spring at intervals of two or four weeks, determinations of the snow cover and its water content are made at regularly established courses in the Contoocook, Pemigewasset, and Winnepesaukee drainage areas. The courses are selected to give a representative sample for the area, having in mind exposure,

ground cover, and altitude. This work is at present being carried on by the U. S. Weather Bureau, the U. S. Geological Survey, the U. S. Engineer Office of Boston, and the Public Service Company of New Hampshire. Every effort is made to get these data into the hands of all interested persons as soon as possible after collection so that they may have a sharp edged tool and not merely an historical record.

In the Connecticut Basin, in addition to regular field parties making trips to established snow courses, the water content is determined weekly by observers at regular rainfall stations.

Mention may be made here of the work now being done by the recently organized Eastern Snow Conference in studying the methods and equipment now in use for sampling snow with a view to recommending a standardized procedure.

HYDROLOGIC ORGANIZATION IN PENNSYLVANIA

The most elaborate flood forecasting service in the United States was set up in the State of Pennsylvania following the disastrous floods on the rivers of that state in March, 1936. The organization of this service was the result of an agreement between the Pennsylvania Water and Power Resources Board, U. S. Geological Survey and the U. S. Weather Bureau.

The difficulties experienced in the past and the objectives sought are set forth in the agreement between the agencies as follows:

"The experience of the Weather Bureau, charged with the responsibility of forecasting floods, indicates that the inability to equitably distribute the cost and benefit of its forecasting service has largely been responsible for the failure to embrace upstream problems in its routine operations. On the lower reaches of the large rivers the Weather Bureau, as a federal agency, is properly functioning in connection with what is without question a national service. As the headwaters are approached, however, the problem becomes localized and it is found more and more difficult to expand an adequate service to upstream points, regardless of their importance. Almost in parallel are to be found the difficulties and cost of a river forecasting service. At the lower river stations of the Weather Bureau accurate and dependable forecasts have been made for many years by the regularly engaged personnel. Here the comparatively slow moving flood crests have made it possible to issue warning sufficiently in advance of their arrival to allow for preparation and evacuation. On the other hand, at or near headwaters, there is not sufficient time after the flood peak

has developed in the stream system to permit the issuance of a forecast or to take advantage of such forecasts in accomplishing an orderly evacuation of doomed areas.

"Because of the comparatively short time available to give notice of an impending flood, the contemplated forecasting service should be closely coordinated with the activities of those agencies whose responsibility it is to evacuate areas lying below predicted flood stages. Likewise, in that the plan for forecasting is identical with that for the operation of flood control systems, the development of the method of flood forecasting should become an integral part of the plans for flood remedial measures. For these reasons the Commonwealth of Pennsylvania proposes to sponsor a project having the following purposes:

1. Through the cooperating agencies to provide the means of inaugurating a modern, scientific river forecasting service throughout the Commonwealth.
2. To establish new sources of basic hydrologic data which are necessary to the program for forecasting and which are indispensable to the design and operation of flood control works.
3. To make available to the Commonwealth of Pennsylvania basic data regarding its surface waters upon which Federal, State, and private interests may be coordinated.

"It is believed, in meeting the first objective, that the needs of the second and third will be provided. Accordingly, it is proposed to establish at Harrisburg a project, the immediate objective of which will be the development of improved flood forecasting methods."

Before this project was started there were six first order Weather Bureau stations located within the state where automatic gages gave continuous records of rainfall. There were also two privately owned gages which provided similar data. With these eight gaging stations as a nucleus, ninety-four additional recording rain gages were installed within the drainage basins of the three primary river systems flowing through the state in such manner that the areal distribution was regular and the area served by each was approximately equal. Installations by other Federal and private agencies increased the total number of recording gages so that by 1940 there were 147 recording gages in operation. The rain gages under the control of the project are visited and serviced at least once a month by an engineer paid by the State of Pennsylvania. Each engineer maintains approximately thirty-two stations. During the winter months these same engineers

collect snow data while on their regular inspection rounds. Upon reaching the hydrologic office, the data recorded on the charts are converted into hourly and daily amounts of precipitation and transcribed on to a regular Weather Bureau form.

At the time of the inauguration of this program, records of stream flow were being collected at ninety locations throughout the state. Instruments recording stream stage were in operation at fifty-three of these stations. At the remainder of the stations, stream discharges were based on twice-daily readings of the stage. To augment the data then being collected, additional recording stations were constructed at a number of locations on streams where stream flow data were considered necessary to the hydrologic studies. Several of the non-recording stations were equipped with recorders and instrument shelters, thus bringing them into the continuous recording class. There are now in operation one hundred stream flow stations throughout the state, seventy-three of which are equipped with recording gages. Funds for the construction of these recording stream flow stations were obtained from Pennsylvania flood control funds, from regular cooperative stream gaging funds, or from P.W.A. allotments made to the Geological Survey.

The Department of Forest and Waters of the Commonwealth of Pennsylvania has a short wave radio network which is available for forwarding precipitation and stream gage data which covers the major portion of the Commonwealth. Daily reports of precipitation and stream flow are received at Harrisburg over the radio network. During times of heavy rains or rapid stream rises a six hourly reporting schedule will automatically go into effect.

The method of forecasting flood heights depends on the particular situation. Much data on past floods and flood heights at critical points on the streams have been accumulated and tabulated or plotted in a usable form. Extensive flood routing studies have also been carried out. It is expected that in times of emergency with a limited personnel the best procedure will be to forecast unit basins and local and tributary areas with unit hydrographs, and route the main river station hydrographs by lagging flows, with a small percentage or no reduction of the peak flow for storage effect in the reach. The stage relations will provide a good check on computed crests but are of less aid in determining time of occurrence.

COMMONWEALTH OF MASSACHUSETTS—FLOOD WARNING AND EMERGENCY ORGANIZATION

In Massachusetts, the Governor has set up a Disaster Committee which is made up of the ranking member of the following departments: Military, Public Works, Public Safety, Public Utilities, Public Health, Public Conservation and the State Division of the Red Cross. The Adjutant General is chairman of this committee. The state is divided into districts and the Adjutant General's office has contact with representative civilians in each district where there has been flood trouble in the past. These representatives in each district are men outstanding in their communities who are connected with organizations interested in the rivers or who have access to information on river conditions. In some cases, at a predetermined gage elevation on the local stream, the man who is responsible for the district telephones to the Adjutant General's office in the State House or to a member of his organization at his home, if the danger arises outside of business hours, to appraise him of the stream elevation and of the emergency situation. As soon as this data begins to come in, a man is stationed at the State House with a chart before him, and the information is marked up as it comes in. If real danger is apparent from the information being sent in, the other departments are notified so that they can first have their men on the alert in the various districts and later go into action as required. Through the interchange of information, worked out through this system, districts down river are appraised of the up river conditions. At the Adjutant General's office the records of gage heights experienced during past floods at the various danger points have been assembled so that knowledge of dangerous elevations is always at hand.

COMMUNICATIONS

Since the flood of March, 1936, and the hurricane and flood of September, 1938, the telephone and telegraph companies have greatly improved their communication lines so that the danger of failures on the lines, similar to those which happened in the past during critical periods, has been decreased. Wires have been replaced by cables and wire and cable lines have been raised above flood levels, or relocated to less exposed places. Auxiliary power service to be used in case of failure of the regular power service has been made more dependable by relocation to higher elevations in the central stations. In addition many

of the electric power companies have installed carrier current communication systems which operate over their transmission lines, and at least one large electric power system has installed a short wave radio system which will be available in case of failure of their telephone lines or transmission lines over which the carrier current system operates. In case of failure of the telephone and telegraph communications system or any part of it, the State Police Department has two-way short wave radio sets in its automobiles which are available for the reception and dissemination of data and warnings.

CONCLUSIONS

Except perhaps in the main river areas near the existing Weather Bureau stations the flood service of the Weather Bureau does not reach the individual, if it reaches him at all, in a manner which justifies his going to the expense of moving his property because the degree of magnitude of the flood is not indicated. If the magnitude of the flood could be stated in terms of water levels and areas likely to be affected, it would be comprehensive and enable the owner whose property is in danger to take necessary precautionary measures intelligently and economically. It is unreasonable to expect the Weather Bureau to undertake such detailed service, not only from the standpoint of cost and employees available, but also due to lack of knowledge of local conditions.

The work of the river operators and other people in New England who are instrumental in gathering and analyzing flood data, will be decidedly benefited if the Weather Bureau can be more specific by indicating more definitely the area to be affected by a given storm, the intensity and magnitude of the precipitation to be expected and conditions of atmospheric circulation likely to prevail. This is considerable to expect, but it is vital information to the organization operating in a given drainage area, and the Weather Bureau is the only organization qualified to give such information.

Outside of the lower Connecticut and Merrimack river basins and parts of Massachusetts where a state organization has been set up, detailed flood warnings to the urban and rural interests should and are likely to continue to originate from the major organization operating in the individual water-shed which may well be termed the unit area. Such organizations should obtain through their nearest local Weather Bureau, all advance information on the probable storm as gathered by the Boston forecasting center, as the local office is best

able to translate the general conditions into terms applicable to the immediate locality. These organizations will then act as their experience indicates is necessary.

Many of the minor streams have a heavy flood producing capacity and resulting damages may be severe and frequent. The needs of people living on such streams may well be handled by the organization operating on the main rivers, of which these streams are feeders. These organizations working in the larger water-sheds could, in many cases with probably very little additional work, become familiar with the smaller adjacent water-sheds so that they would be able to give such warnings as may be necessary. The coastal streams falling between the larger basins might be covered in the same way.

The organization disseminating flood warnings must, of necessity, have in its files adequate data on the location of danger zones for floods of varying magnitude, the extent of possible inundation for floods of given heights, the nature of the damage which may occur, and above all, the names of key men, and the details of how they may be reached on short notice. River profiles and topographic maps with danger zones laid out thereon are essential basic data in coordinating incoming flood data and issuing intelligent orders or warnings.

The test of the value of a comprehensive and effective flood warning service is its ability to deliver flood warnings to urban and rural centers wherever located and especially to organizations and individuals whose property may be in the danger zone. The contact, to be effective, must be directly with the person whose property is in danger or some individual responsible for such property. It must be reasonably specific as to the probable height to which the water may be expected to rise. It must set forth the probabilities of ice jams or any other interference with normal run-off conditions. It should in any event be as timely as possible, because time is often the essence of avoiding loss of life or property damage.

Such storms and floods as those which occurred in March, 1936, and September, 1938, are likely to destroy telephone and telegraph lines as well as transmission lines, although the power companies who operate carrier current sets and telegraph and telephone companies have eliminated many of the danger points. When lines of communication fail, the only effective agency for receiving and disseminating flood information is the radio. The State Police Departments have cars equipped with two-way short wave radio sets. There are many amateur short wave radio sending and receiving stations and one or

more of the larger power companies have installed a short wave radio network. All of these are available for flood emergency warnings, and drills for work of this kind have been carried on.

RECOMMENDATIONS

The committee does not see the need for any radically new organization for gathering flood data and disseminating warnings in New England. A very elaborate and expensive set-up sponsored by state and federal bureaus, such as is now operating in Pennsylvania, may be justified there for the protection of the large number of people and industries in their cities close to the great rivers which are threatened nearly every year in different degree, but in New England the situation does not seem to warrant that kind of an organization.

The facilities now existing, though varying considerably in different states, are adequate if properly handled and extended to take care of some of the outlying areas on the smaller streams. Every effort should be made to keep the existing organizations on the alert and ready to function at all times.

Individuals and business organizations, who own or are responsible for property subject to flood damage, should be and are charged with the duty to acquaint themselves with elevations and flows which are dangerous to properties in which they are interested. It is especially important that they know the depth of water over and the area of the property that will be affected by any given stage or flow to the end that they may be able to properly interpret flood warnings when they are given.

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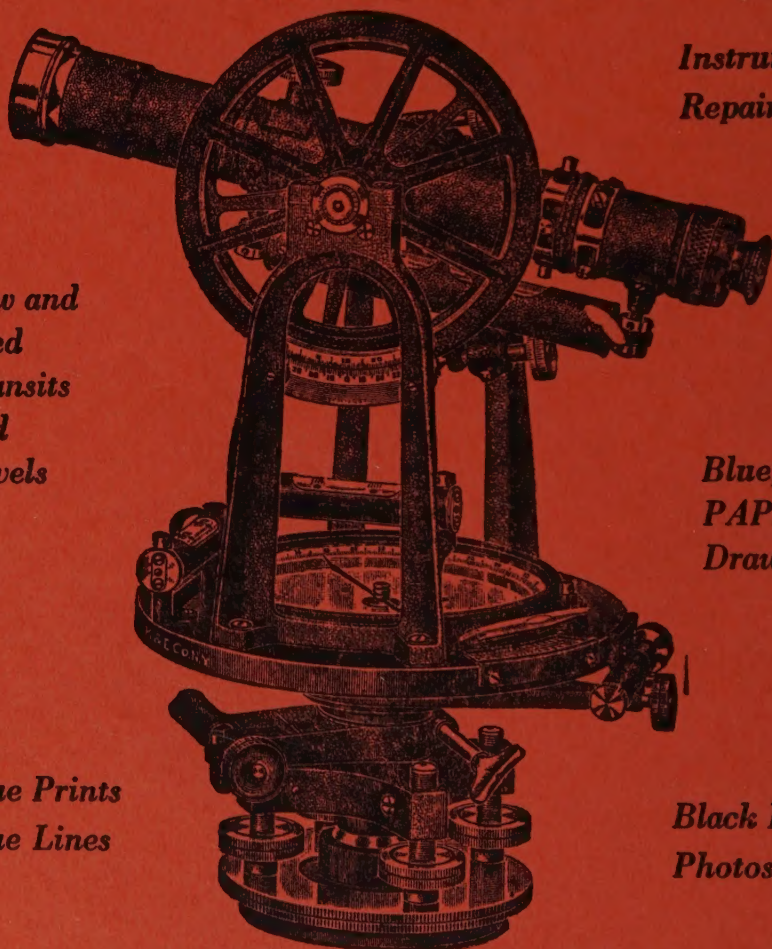
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